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NORTH ATLANTIC TREATY ORGANISATION

RESEARCH AND TECHNOLOGY ORGANISATION

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RTO TECHNICAL REPORT 61

Collaboration for Land, Air, Sea, and Space Vehicles: Developing the Common Ground in Vehicle Dynamics, System Identification, Control, and Handling Qualities

(La collaboration dans le domaine des véhicules terrestres, aériens, maritimes et spatiaux: L'établissement d'une approche commune de la dynamique des véhicules, l'identification des systèmes, et les qualités de contrôle et de pilotage)

Work performed by the RTO Systems Concepts and Integration Panel (SCI).

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RTO is the single focus in NATO for Defence Research and Technology activities. Its mission is to conduct and promote cooperative research and information exchange. The objective is to support the development and effective use of national defence research and technology and to meet the military needs of the Alliance, to maintain a technological lead, and to provide advice to NATO and national decision makers. The RTO performs its mission with the support of an extensive network of national experts. It also ensures effective coordination with other NATO bodies involved in R&T activities.

RTO reports both to the Military Committee of NATO and to the Conference of National Armament Directors. It comprises a Research and Technology Board (RTB) as the highest level of national representation and the Research and Technology Agency (RTA), a dedicated staff with its headquarters in Neuilly, near Paris, France. In order to facilitate contacts with the military users and other NATO activities, a small part of the RTA staff is located in NATO Headquarters in Brussels. The Brussels staff also coordinates RTO's cooperation with nations in Middle and Eastern Europe, to which RTO attaches particular importance especially as working together in the field of research is one of the more promising areas of initial cooperation.

The total spectrum of R&T activities is covered by the following 7 bodies:

- AVT Applied Vehicle Technology Panel
- HFM Human Factors and Medicine Panel
- IST Information Systems Technology Panel
- NMSG NATO Modelling and Simulation Group
- SAS Studies, Analysis and Simulation Panel
- SCI Systems Concepts and Integration Panel
- SET Sensors and Electronics Technology Panel

These bodies are made up of national representatives as well as generally recognised 'world class' scientists. They also provide a communication link to military users and other NATO bodies. RTO's scientific and technological work is carried out by Technical Teams, created for specific activities and with a specific duration. Such Technical Teams can organise workshops, symposia, field trials, lecture series and training courses. An important function of these Technical Teams is to ensure the continuity of the expert networks.

RTO builds upon earlier cooperation in defence research and technology as set-up under the Advisory Group for Aerospace Research and Development (AGARD) and the Defence Research Group (DRG). AGARD and the DRG share common roots in that they were both established at the initiative of Dr Theodore von Kármán, a leading aerospace scientist, who early on recognised the importance of scientific support for the Allied Armed Forces. RTO is capitalising on these common roots in order to provide the Alliance and the NATO nations with a strong scientific and technological basis that will guarantee a solid base for the future.

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Collaboration for Land, Air, Sea, and Space Vehicles: Developing the Common Ground in Vehicle Dynamics, System Identification, Control, and Handling Qualities

(RTO TR-061 / SCI-053)

Executive Summary

This technical report is the culmination of the SCI-053 Task Group – Vehicle Dynamics, System Identification, Control and Handling Qualities. Over three years, this group held a series of meetings between experts on tanks, trucks, aircraft, helicopters, ships, submarines and satellites. They addressed the various technical areas identified in the name of the task group, exploring the similarities and differences between their respective vehicles and striving to identify areas where collaboration between experts would be the most valuable.

Over the course of these meetings, the discussions demonstrated the significant differences between these vehicles, owing to their operational environments, military role or even just plain physics. On the other hand, at times the discussions concerned issues where the word “tank” could be easily replaced by “truck”, “aircraft”, “helicopter”, “ship” or “submarine”, and yet the meaning, implications and value of the statements were equally valid. A significant stumbling block during the process was a lack of commonly held terminology, definitions and perceptions regarding key concepts. However as the meetings progressed, this “common-ground” was developed. Particularly fruitful discussions took place regarding handling qualities, during which all participants acknowledged the importance of vehicle “ease of use”. Yet, the level of rigor applied to this area seems to vary widely between vehicle types and the term “handling qualities” itself seems to be commonly used only for air vehicles. In this and other cases, however, when the commonly understood terms were established, the discussion revealed how similar many technical challenges are between vehicle environments.

This report summarizes the wide-ranging discussions of this group. In chapters dedicated to each of the four technical domains, the report presents the concepts, key features, similarities, and differences between vehicles for the four environments. This generalist-level summary provides the vehicle expert of one environment a sufficient background on the other vehicle environments, so that meaningful discussions towards effective technical collaboration can be initiated. The material throughout the report is summarized in the final chapter and highlights a variety of common challenges that could be the initial targets of such collaboration.

On the basis of the discussions of SCI-053 Task Group and draft versions of this report, an RTO-SCI Panel Symposium entitled “Challenges in Dynamics, System Identification, Control and Handling Qualities for Land, Air, Sea, and Space Vehicles” was developed for Berlin, Germany in May 2002. All efforts to date indicate that the potential of meaningful, effective collaboration on technical issues of common interest to all four military environments is high, and it is hoped that this report and the associated symposium will further support and foster such activity.

La collaboration dans le domaine des véhicules terrestres, aériens, maritimes et spatiaux: L'établissement d'une approche commune de la dynamique des véhicules, l'identification des systèmes, et les qualités de contrôle et de pilotage

(RTO TR-061 / SCI-053)

Synthèse

Ce rapport technique représente l'aboutissement des travaux du groupe de travail SCI-053 sur la dynamique des véhicules, l'identification des systèmes, et les qualités de contrôle et de pilotage. Au cours de son mandat de trois ans, ce groupe a organisé une série de réunions de spécialistes sur les chars, les camions, les aéronefs, les hélicoptères, les navires, les sous-marins et les satellites. Les membres du groupe ont traité des différents domaines techniques en examinant les similitudes et les différences entre les véhicules respectifs et en s'efforçant d'identifier les domaines où la collaboration entre spécialistes serait le plus profitable.

Les discussions qui ont eu lieu lors de ces réunions ont démontré les différences importantes qui existent entre ces véhicules en raison soit de leurs environnements opérationnels, soit de leur rôles militaires, soit tout simplement de la physique. En revanche, les discussions ont parfois concerné des questions s'appliquant à l'ensemble des véhicules, sans distinction d'environnement opérationnel. Le manque de terminologie, de définitions et de perceptions communes concernant les concepts clés a été la principale pierre d'achoppement pour les participants. Cependant, au fur et à mesure du déroulement des réunions, une approche commune s'est dégagée. Des discussions particulièrement fructueuses concernant les qualités de pilotage ont eu lieu, lors desquelles l'ensemble des participants se sont accordés à reconnaître l'importance de la "facilité d'utilisation" des véhicules. Pourtant, le degré de rigueur appliqué dans ce domaine semble varier beaucoup entre les différents types de véhicules et le terme "qualités de contrôle et de pilotage" lui-même ne semble s'appliquer qu'aux véhicules aériens. Cependant, dans ce cas particulier, comme dans d'autres, une fois que les termes avaient été définis d'un commun accord, les discussions qui ont suivi ont démontré la similitude qui existe entre les nombreux défis techniques posés par les différents environnements de véhicules.

Ce rapport résume les discussions tous azimuts de ce groupe. Il consacre un chapitre à chacun des quatre domaines techniques afin de présenter les concepts, les caractéristiques clés, les similitudes et les différences entre les véhicules pour les quatre environnements. Volontairement non spécialisé, il est susceptible d'apporter aux spécialistes de l'un des environnements suffisamment d'informations sur les autres pour permettre l'organisation de discussions valables, susceptibles de déboucher sur une collaboration technique efficace. Le chapitre final du rapport propose un résumé des débats et met en évidence un certain nombre de défis communs pouvant faire l'objet initial d'une telle collaboration.

En prenant comme point de départ les discussions du groupe de travail SCI-053 et les versions préliminaires de ce rapport, un symposium RTO-SCI sur "Les défis dans les domaines de la dynamique, l'identification des systèmes et les qualités de contrôle et de pilotage des véhicules terrestres, aériens, maritimes et spatiaux" a été préparé en vue de son organisation à Berlin, en Allemagne au mois de mai 2002. Tous les efforts consacrés à ce sujet jusqu'à présent indiquent qu'il existe de réelles possibilités pour une collaboration valable et efficace sur des questions d'intérêt commun pour les quatre environnements militaires, et il faut espérer que ce rapport, ainsi que le symposium qui y est associé serviront de soutien et d'encouragement supplémentaires à cette activité.

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Preface

The SCI-053 was initiated during the final meeting of the Dynamics and Handling Qualities Sub-Committee of the AGARD Flight Vehicle Integration Panel in the Fall of 1997. At that time, with the upcoming redistribution of AGARD and DRG resources into a new, multi-environment (land, air, sea and space) organization, the RTO, it was felt that the network of experts in the aerospace vehicle dynamics and handling qualities could serve as the starting point for a far wider network of experts covering all four vehicle environments. This was the central theme of a proposal for a task group concerned with vehicle dynamics, system identification, control and handling qualities that was assigned four objectives:

a) To develop annual reports of technical activity on the topic area.

b) To consider the similarities in the techniques and skills that are applied to study, analyse and design land, sea and air vehicles in the areas of dynamics, mathematical identification and modelling, control and handling qualities. If warranted, the group would also commence to build mechanisms that assist in the co-ordination and integration of the three environments in these technical areas.

c) To develop proposals for future RTO/SCI activities.

d) To develop a directory of NATO experts and practitioners in the fields of flight dynamics, system identification, control and handling qualities.

An exploratory team was established and met during an AGARD legacy activity in Madrid during the Spring of 1998 to further develop this premise. The resulting proposal was accepted by both the newly formed Systems Concepts and Integration Panel in the Fall of 1998 and later by the RTO Research and Technology Board in the Spring of 1999. The resulting SCI Task Group 053 met six times over the next three years:

Spring 1999 – RTO Headquarters, Paris, France
Fall 1999 – US Army Tank-automotive and Armaments Command, Warren, Michigan
Spring 2000 – Maritime Research Institute Netherlands, Wageningen, The Netherlands
Fall 2000 – The Flight Research Laboratory, NRC, Ottawa, Canada
Spring 2001 – BAE Systems Marine Ltd., Barrow-in-Furness, UK
Fall 2001 – University of the Federal Armed Forces, Hamburg, Germany

During the course of these meetings, this dedicated task group met all of its objectives, highlighted by the clear realization that collaboration between experts in different environments has great potential, the publication of a multi-environment expert data base, the development of an SCI Symposium on the topic areas (Germany, Spring 2002) and this report, which demonstrates many of the similarities that can be exploited in future collaboration.

As the Chairman of this group, I wish to thank all of the SCI-053 members, their supporting organizations and the organizations which hosted our series of meetings and gave us exceptionally educational tours of their facilities. It has been a rewarding five years.

Stewart Baillie
April 7, 2002

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Chapter 1 – Introduction

1.1 BACKGROUND

In today's economic environment, military forces must continually balance the life cycle and acquisition costs of their assets against the requirements for a flexible, operational force structure. Military vehicles employed by the land, air, sea, and space forces are a significant part of the overall force structure and clearly enable flexibility and responsiveness. On the other hand, they are significant cost drivers for most countries. How these vehicles are designed, supported, and operated has a significant effect on the both the financial and operational elements of a nation's defensive capability. As numerous studies have shown, decisions made during the design cycle of a vehicle can have a tremendous impact on the overall cost of acquisition and on those costs that accumulate over its life cycle. The technologies applied to solving problems that arise during a vehicle's service life can also make major changes in its effectiveness and life cycle cost. Clearly, effort spent on the improvement and consolidation of vehicle technologies can pay off in both the short-term and the long-term.

To continue the trend of NATO military force superiority, the Research and Technology Organization, RTO, is tasked to foster the technical strength of the member nations. Through the sharing of technical development experience, significant cost savings and gains in operational effectiveness are possible. This sharing of experience, through a network of technical experts, minimises duplication, serves to identify national competencies and weaknesses, and provides the basis for the initiation of activities which address identified weaknesses. Of equal importance, the RTO network of technical experts can be employed to address near-term issues and requirements as they arise.

The emergence of RTO as a NATO organisation to co-ordinate research and technology activities over the breadth of the military environments (land, air, sea, and space) has presented a unique challenge. While the former Advisory Group for Aerospace Research and Development (AGARD) addressed aerospace issues, the three other operational environments, land, sea, and space, were much less represented in the formal NATO bodies that became the RTO. Developing a solid representation from all operational environments, coupled with making the technical experts of each environment more aware of their counterparts, is a near-term goal of the RTO. It is expected that this consolidation of experts will result in valuable technical advances and synergies.

The technical areas of vehicle dynamics, system identification, control, and handling qualities form a core competency upon which the design and development of any military vehicle is based. Application of vehicle dynamics, modelling, and system identification expertise results in a mathematical understanding of the vehicle performance and dynamics and provides analysis tools of great advantage. Control expertise is used to make the necessary design trade-offs between vehicle stability and control and, as exemplified by today's ever expanding usage of fly-by-wire technology in aircraft, this expertise can radically alter the operational capability and useable performance of the vehicle. Finally, the consideration of handling qualities issues can assess the true impact of vehicle dynamic characteristics on its operational effectiveness and can lead to substantial improvements when these issues are considered initially in the design process.

Military vehicles of today are vastly more complex than their predecessors in terms of systems, roles, and missions. The growth in understanding, coupled with increased analytic capability in each of the technical areas addressed here, provides numerous opportunities to improve the processes employed in their design and operation. The development and application of new techniques is leading to a better understanding of how this expertise can enable a synergistic approach to problem solving. Continued development of the core competencies is essential to harness these technological advancements and to achieve more cost-effective systems.

NATO experts in the aerospace domain who work in the areas of dynamics, system identification, control, and handling qualities have counterparts addressing land, sea, and space vehicle issues. These experts, at times, face similar challenges and it is probable that many of today's techniques and competencies can be applied with equal benefit in all four operational environments. Such collaboration could lead to new understanding, to improved solutions to today's most challenging problems, and, overall, could greatly improve the cost effectiveness of each vehicle type.

The RTO SCI – 53 technical team was formed to address this idea and specifically attain the following objectives:

a) Provide a forum where technical activity on the topic areas of vehicle dynamics, system identification, vehicle control, and handling qualities is reviewed and reported.

b) Consider the similarities in the techniques and skills that are applied to study, analyze and design land, air, sea, and space vehicles in the topic areas. If warranted, the group would also commence to build mechanisms that assist in the co-ordination and integration of the experts in these areas.

c) Develop proposals for future RTO/SCI activities.

d) Develop a directory of NATO experts and practitioners in the fields of vehicle dynamics, system identification, vehicle control, and handling qualities.

1.2 PURPOSE

This report addresses the second goal of the SCI-53 technical team, namely to build mechanisms to assist the co-ordination and integration of experts working in the different operational environments. The report provides NATO personnel and subject matter experts a preliminary review of the issues involved in vehicle dynamics, modeling and system identification, control, and handling qualities as these topics apply to modern military vehicles in all four environments. By focussing on the commonalties and differences between the four environments, this report will also serve to highlight areas of potential collaboration between experts from the various technical communities. While the solution for a particular problem of a tank, ship, submarine, fixed-wing aircraft, helicopter, or satellite is not expected to be exactly applicable to another vehicle type, the similarities in highlighted problem areas, the similarities in methods used, and the uniquely different approaches that will arise from experts with different points of view will provide insight that will lead to significant cost reductions and enhanced operational effectiveness.

1.3 SCOPE

This report is confined to address military vehicles in each of the four operational environments. While non-military vehicles are not expressly excluded from these discussions, no attempt is made to fully cover the issues of civil vehicles. On the other hand, it is assumed that dual-use technologies and best industrial practices are intrinsically a part of both civil and military vehicle design and are therefore reflected in all aspects of this report.

Obviously the breadth of the technical areas and domains represented by the membership of SCI-53 provided further constraints to the scope of the work. While the group membership became more broadly based over the group's tenure, and technical visits to a variety of research organisations resident in NATO nations provided a significant addition to the technical awareness of the team members, certain biases and technical emphasis arising from the members specific technical points of view are reflected in this final report. In addition, the report considers only those issues and problems that are currently under study or consideration in the various organizations and nations represented, and does not try to predict more general future requirements or technical issues.

The report is structured to consider each of the four technical areas in turn:

- Chapter 2: Vehicle Dynamics,
- Chapter 3: Vehicle Modeling and System Identification,
- Chapter 4: Control of Vehicles and Vehicle Systems
- Chapter 5: Vehicle Performance and Handling Qualities

Each of these chapters is developed to illustrate the similarities and differences between the various types of vehicles and strives to highlight areas of commonality and current technical challenges. Following these four chapters is the final chapter that draws together conclusions regarding the material presented in the body of the report. The report concludes with several appendicies containing technical material of interest:

- Appendix I describes research facilities in use in the various nations represented by the SCI 53 technical team.
- Appendix II provides a brief overview of the application of intelligent systems in land vehicles.
- Appendix III describes crew stations and steering elements of land vehicles.
- Appendix IV provides a glossary of abbreviations used in the report.

Chapter 2 – Vehicle Dynamics

This chapter presents an overview of the vehicle and environmental characteristics that contribute to successfully modelling and controlling vehicle dynamic behaviour. It is deliberately broad in scope in order to provide a context for the issues discussed in greater detail in subsequent chapters. Similarities and differences between environments are indicated where obvious; however, a final assessment of where commonalties in technology exist, and can be exploited, is reserved for the concluding discussion in Chapter 6.

2.1 BACKGROUND – Vehicle Dynamics in the Design Process

Global economic trends are making all manned military vehicles high value platforms. In consequence, there is pressure for the balance between cost, survivability, safety, and combat effectiveness to shift away from the last. In vehicle dynamics, as in other technologies, continuing work is needed to offset this tendency.

The dynamics of a vehicle type influences the formal vehicle design process in numerous ways. For ships, the process is commonly represented by the design spiral [Evans, 1959] shown in Figure 2.1 (however, other methodologies have been advocated [Vassalos,1999]). The spiral illustrates progressive iterations, in increasing detail, from requirements to a final design, which eventually result in the full definition of the ship characteristics (dimensions, hull form, etc.). At each stage, the dynamics, principally pertaining to hull form, seakeeping, propulsion, stability, and performance, must be estimated and refined, using an appropriate mix of numerical estimation, simulation, and experimental testing. From contract design to construction, to acceptance, there are additional inner loops of the spiral, although only certain design aspects, such as stability and performance, may be addressed. However, these aspects are strongly related to the ship's hydrodynamics, and may involve extensive trials and simulation.

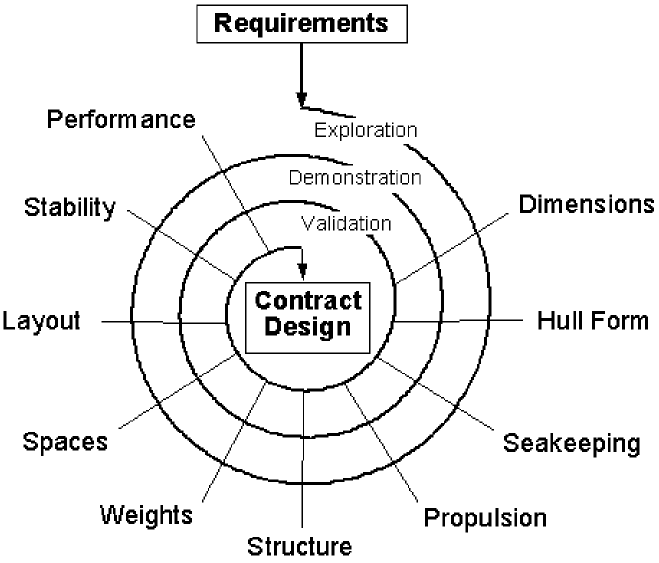


Figure 2.1 - The ship design spiral.

Unlike for land and air vehicles, the economics of ship production do not, with very few exceptions, allow prototyping a new design. Consequently, a formal process such as outlined in figure 2.1 is generally rigorously adhered to for ships, and, since it relies heavily on prior experience, advances in capability and performance are thereby evolutionary rather than revolutionary. Nevertheless, the first-of-class may become a *de facto* test-bed for future improvements, especially in such areas as propulsion and manoeuvring.

Military ground combat vehicles have grown significantly in weight to be more survivable. This has adversely impacted their transportability on aircraft and naval vessels. Considerable effort is now being applied to reduce overall ground vehicle weights without compromising both survivability and structural integrity. While generally maintaining operational speeds, fighter aircraft with both interceptor and ground support capabilities have grown significantly in weight and complexity. The fewer numbers of military ships and aircraft has resulted in a higher reliance on “multi-role” requirements, leading to design compromises and the need for higher availability (often in the face of hostile environmental factors). For destroyers and frigates, the adoption of one or more helicopters as part of the system alleviated the need for high speed and manoeuvrability, but introduced interoperability issues requiring, amongst other things, improved seakeeping and short-term motion forecasting. Differing manoeuvring requirements for different missions, or different aspects of a role, also require compromises in capability, Figure 2.2.

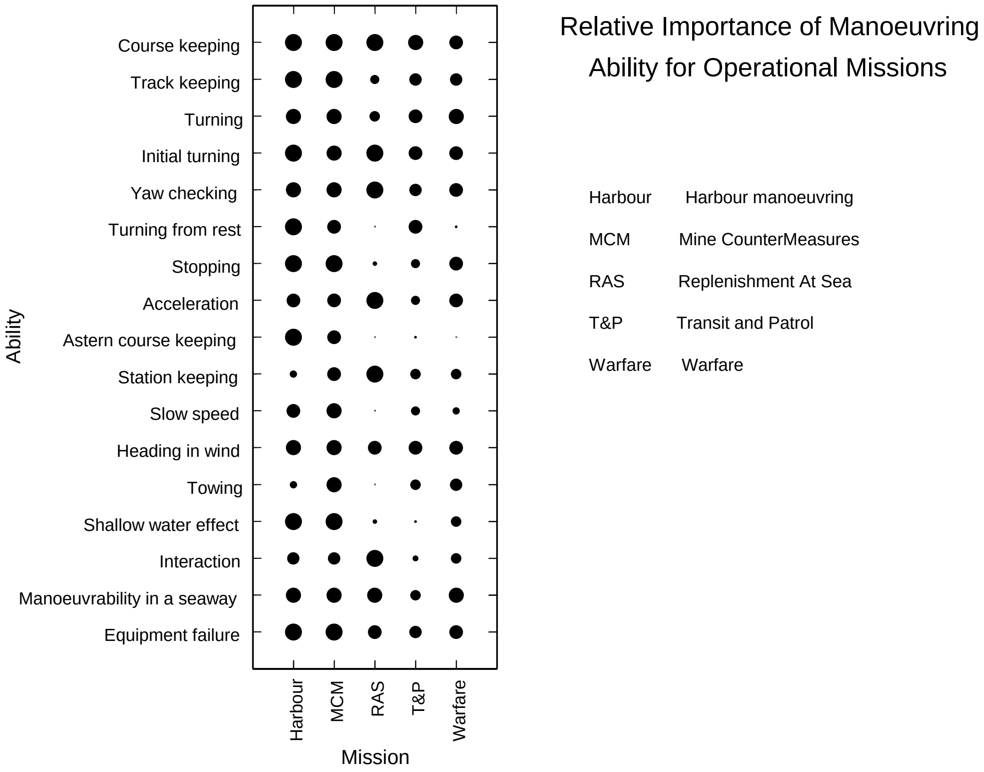


Figure 2.2 - A typical ranking of warship manoeuvring ability for its importance to various missions.

Civilian manned vehicles range considerably in value, and the dynamics and other design aspects must strike a balance between vehicle safety and economics. Although more-or-less rigorous safety requirements are legislated for all environments, the economics of acquisition and operation drive vehicle design at least as much as safety requirements. This difficult balance of constraints is being increasingly seen in military acquisitions, at least of non-“sharp-end” vehicles and systems, which may be based on commercial rather than military specifications.

In contrast, the dynamics of unmanned vehicles, both military and civilian, are often primarily driven by specialised mission requirements. Nevertheless, their performance is likely to be constrained by vehicle size, power, and/or endurance. Many unmanned vehicles are now required to perform complex autonomous missions of long duration.

2.2 GENERAL VEHICLE CHARACTERISTICS

Some examples of vehicles and systems (both military and civil) from each of the four environments are given in Table 2.1. Within categories, the vehicles are listed in approximate order of mass, heaviest first.

Representative time scales (*L/U*, where *L* is typically length, and *U* is forward speed) and masses for some vehicle categories of interest are compared in Figure 2.3. Since this is a variation of the classic transport efficiency diagram, the two variables are reasonably well correlated for each vehicle category. However, there is some distinction between the ranges for military and civilian fixed-wing aircraft, because of speed, and between military and civilian surface ships, because of mass.

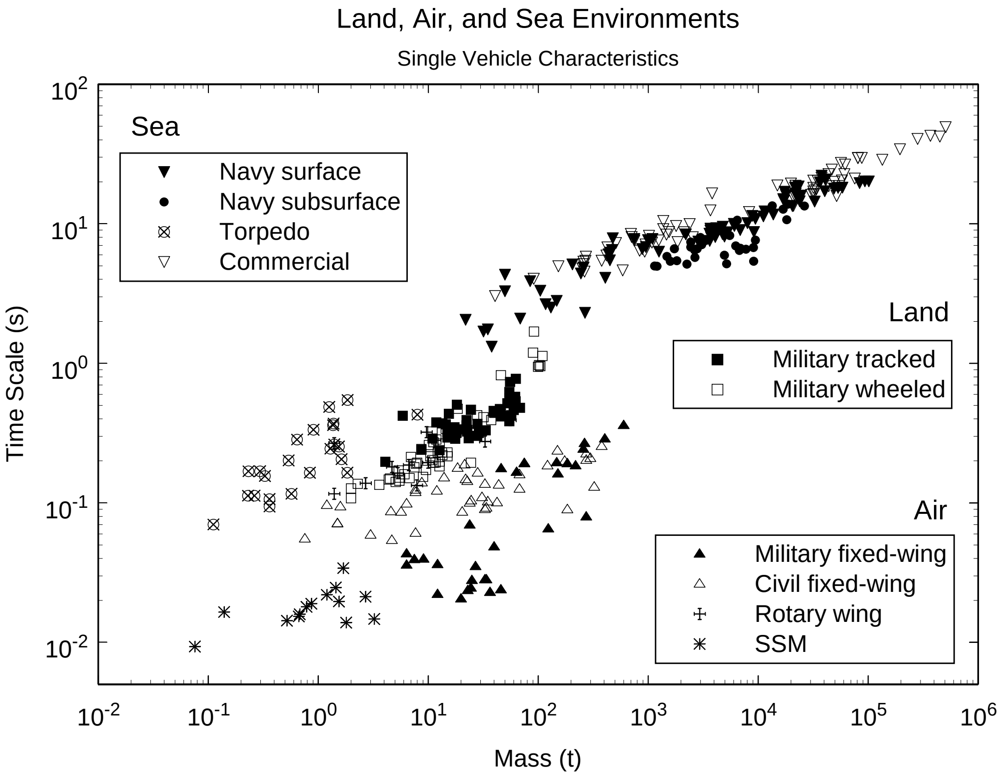


Figure 2.3 - Time scales (sec) and masses (tonnes) of some representative vehicle types in the land, air, and sea environments.

Table 2.1 - Representative vehicle types.

Land	**Air**	**Sea**	**Space**
Tracked: Main Battle Tank Light tank SP artillery Heavy construction Bridgelaying Recovery, Engineering Mine clearing APC, Command Wheeled: Tractor-trailer Truck Reconnaissance APC, Command Trailer, Towed gun Ambulance Car, Utility Rail Specialised: Recreational Over-snow Amphibious	Fixed wing: Heavy lift Bomber Tanker Large transport Regional transport Fighter Ground support Reconnaissance Training Commuter, light Agricultural Recreational Sailplane, Ultra-light Missiles Cruise, SSM SAM Tactical ballistic Rotary wing: Heavy lift Ground support Transport Scout/attack Towed systems: Sailplane launch Antenna MAD drone, Target Specialised: Lighter-than-air WIG Freefall Parachute	Surface: ULCC, VLCC CV, CVN Bulk, General cargo RO/RO, Container Cruise, Ferry CG, DD, FF Auxiliary, Hospital Coastal, Service MCM, Patrol Fishing Planing craft Recreational Subsurface SSBN, SSN, SSK Special operation UUV, ROV Torpedo Air/ship launched Towed systems: Cable arrays Sonar fish Specialised: Semisubmersible Multi-hull ACV, SES Hydrofoil Buoyant/freefall	Transit: Shuttle Spaceplane LR ballistic missile Re-entry vehicle Space-Based: Satellite Space station

There are a number of other different time scales to consider; if *L/U* represents a medium length time scale for a particular vehicle then these other time scales can include:

- Time to complete a representative manoeuvre — typically long scale.
- Vehicle responses — roll period, etc.: typically medium scale.
- Time history (memory) effects — trailing vortex interactions, etc.: typically medium.
- Vehicle subsystem responses — land vehicle suspension period, etc.: typically short scale, but can vary considerably.
- Sensing and control system responses — short to very short scale.

In a few cases, subsystem characteristic time scales e.g., that of a tow cable, may be much longer than that of the vehicle(s) in the system.

Time scales impact all of the technologies discussed in this report, and particularly those involved in simulation and modelling. Including the full control bandwidth will generally add one or two lower orders of magnitude to time scales in a simulation. Such a variation, or even the variation in fundamental time scales in a multi-vehicle simulation, will result in “stiff” equations of motion that require relatively inefficient and complex implicit methods to integrate.

Vehicle mass is normally an indicator of acceleration response to excitation; as depicted in Figure 2.3, the vehicle masses under consideration here span seven orders of magnitude. Military vehicles, however, typically operate up to the limits of the human performance envelope, so upper acceleration limits for most vehicles may, in practice, be similar for quite different types of manned vehicles. Fighter aircraft are a notable exception since there is enhanced acceleration tolerance for the pilot when wearing a G-suit (which then functions as a system of the aircraft, providing protection to the operator).

The rest of this section lists various aspects of vehicle dynamics in the absence of external excitation. External excitations are addressed in Section 2.3.

2.2.1 Manoeuvring Dynamics of a Single Vehicle

For simple manoeuvring simulations, representations of only the rigid body dynamics may suffice. However, the coupling of compliant and rigid body modes is becoming increasingly important in all environments because of lighter, and more flexible, structures and active sub-system control. The trend towards lighter structures is notably significant for large aircraft, and is a primary consideration for space vehicles. Modelling structural response in conjunction with dynamic analysis is critical for specifying and quantifying structural loads, fatigue, reliability estimates, and for making assessments of noise, vibration, and ride quality.

In the course of a manoeuvre, inertial forces are usually significant and, in general, reasonably easy to predict. Excluding, for the moment, external excitation, some of the other principal dynamic modes and forces on a vehicle include:

Land: Body flexibility, passive and active suspension, variable wheel load and traction, aerodynamic drag. Rail vehicles have constrained trajectories.
Air: Wing and control surface flexibility, aerodynamic forces (drag, damping, crosscoupling, etc.), interaction with the ground during takeoff and landing, changes in mass due to fuel burn, weapons release or deployment of cargo.
Sea: Hull flexibility, hydrodynamic forces (drag, damping, crosscoupling, added mass forces, etc.), hydrostatic forces.
Space: Flexibility of structure, coupling of large propulsive forces.

Fluid dynamic forces result in some degree of commonality between the sea and air environments; the unique features of each are summarised in Section 2.7.2.

2.2.2 Extreme Manoeuvres

Modelling the dynamic modes and forces listed in the previous section is in most cases straightforward for small and moderate manoeuvres. It is generally more difficult for extreme manoeuvres such as:

Land: Small-radius turns, high speed lane changes, steep gradients, side slopes, extreme terrain variations, high acceleration/deceleration.
Air: High angle of attack non-linear flight dynamics (aerodynamic stall, stall-departure, post-stall), high angular rates, VTOL, STOVL, etc.
Sea: Small-radius fast turns, submarine emergency recovery (fast buoyant ascent), crash-back and crash-forward, manoeuvres or conditions resulting in local flow separation, cavitation, or ventilation.

Helicopters provide a special set of extreme manoeuvres where the dynamic characteristics of the vehicle change radically with time and airspeed. Examples of these include the common transition from hovering to forward flight, the transition back to hovering flight, and transitions to and from autorotative flight. Precision landings in general, and particularly slope landings create further problems where aircraft dynamics alter with altitude above ground and the nature of the control problem changes abruptly as the helicopter landing gear start to contact the ground.

One complication for simulating extreme manoeuvres such as looping an aircraft is that the conventional Euler equations of motion contain singularities where the vehicle (or a system component) axis becomes vertical in an earth-fixed inertial axis system. The solution is to cast vehicle rotations in a four parameter (e.g., quaternion or Cayley-Klein) representation [Phillips *et al.*, 2000]. This is standard for land and air vehicle simulations, but normally done for sea vehicles only in simulations in which the vehicle approaches capsize.

In some cases, a vehicle is required to change environments in the course of a mission. From the points of view of both the designer and operator, this may be a difficult, if not an extreme, manoeuvre, and it is generally complex to model and simulate. Examples include floatplane and seaplane takeoff and landing (or water scooping for firefighting amphibian aircraft), and amphibious vehicle landfall and departure.

2.2.3 Multiple Coupled Units

This category comprises vehicles that are hard-coupled together with a semi-rigid or rigid connection that has only a few degrees of freedom. There is often additional strong coupling between the component vehicles arising from proximity interactions.

Examples are found chiefly in the land environment, and include permanently or semi-permanently articulated vehicles such as tractor-trailers, truck-trailer tows, rigid-tow vehicle recovery, trains (rail or truck trains), and mine clearing systems and detonators (these being pushed rather than pulled). Pushing an aircraft out from the ramp is a purely land problem where the suspension characteristics of the larger, pushed, vehicle are primarily derived from a quite different set of criteria — aircraft landing. At sea, primarily in inland waters, hard-coupled tug barge (or barge-raft) combinations are frequently used, with the tug pushing. Another example, this time in the air vehicle environment, is the dynamics of aerial refuelling, whether by boom or by probe and drogue. In addition to the dynamics of the connection between the two vehicles, this case requires that the flow field interference of the tanker on the receiver must be evaluated. In some extreme cases for newer aircraft, special control system modes are used for aerial refuelling.

2.2.4 Towed Systems

The term “towed systems” is used here for systems that are characterised by soft mechanical coupling with flexible connections that have several degrees of freedom — typically a cable that transmits force only in tension. Examples include:

Land:	Flexible tows for vehicle recovery, crane/winch operations.
Air:	MAD (magnetic anomaly detection) birds, decoys, target drogues, antennae, single or multiple helicopter slung load work (e.g., coupling between cable, payload and helicopter dynamics), sailplane launch, parachutes.
Sea:	Towed sonar “fish”, flexible arrays and array systems, casualty recovery by tug or other vessel, barges and barge trains, offshore structures.

Modelling towed systems can be simplified if the dynamics of the towing and towed vehicles or systems are decoupled. This typically occurs in the sea environment for large towships with relatively small tows; i.e., the larger towship is not significantly influenced by the tow forces on it, and can be simulated separately, providing a predetermined towpoint trajectory. However, there are many cases in which this simplification cannot be made, e.g., in sea minehunting systems, where the towed and towing vehicles are of comparable size. The towed object may also be much larger than the tow ship, e.g., barges, offshore structures, and ocean survey systems consisting of several parallel arrays each several km long.

Numerical complications for towed system simulations include handling stiff equations of motion since the dynamic time scales of the cable(s) and vehicles are quite different. There will also be Euler-rotation singularities for vertical cable segments, and discontinuities occur if the cable goes slack.

2.3 EXTERNAL INTERACTIONS

2.3.1 External Excitation

The most familiar, and often a very significant, contribution to external excitation forces results from a variety of environmental disturbances ranging from near-harmonic perturbations to broadband noise. These factors include:

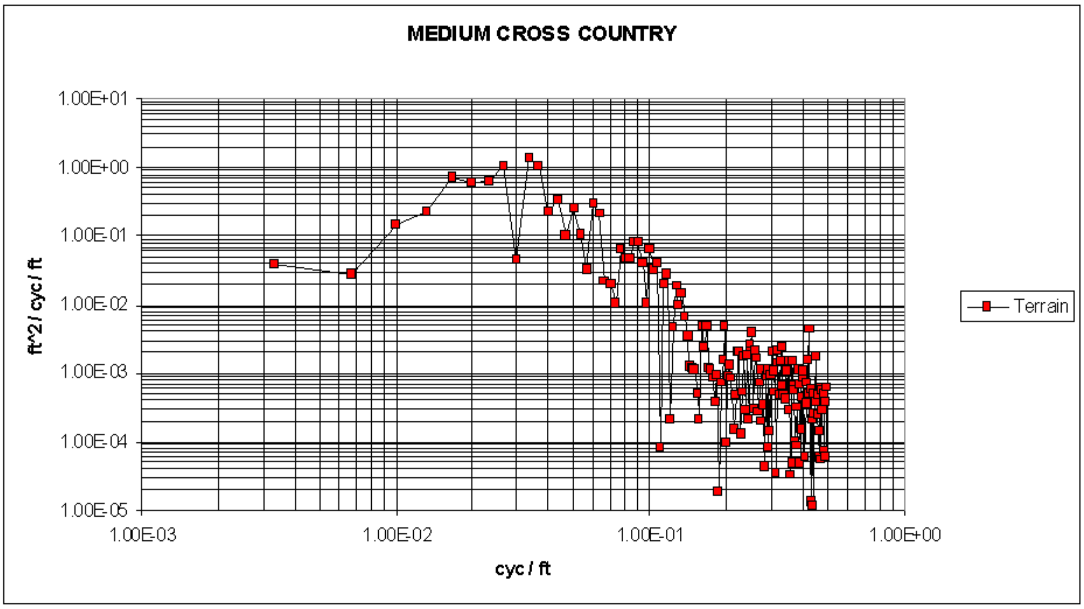
Land: On and off-road surfaces and terrain types (paved and unpaved roads, mud, sand, snow, cross country surface roughness, slopes and obstacles), weather (dry, wet, snow, and ice), wind forces.
Air: Turbulence, gusts, windshear, ice.
Sea: Seastate, wind forces, current, ice.

Typical examples follow. In addition to these environmental disturbances, military land, air, and sea vehicles are all subject to high transient forces from blast and weapon recoil.

2.3.1.1 Land

For military vehicles, terrain unevenness is characterised by its surface spectral density. This relates to the driving speed limit not only through the traction forces but also through operator-related limits such as ride quality (e.g., acceleration at the driver’s seat). Figure 2.4 illustrates surface spectra for medium and rough off-road surfaces.

Raw terrain profile data are usually collected using a rod-and-stadia-level on a sample of the terrain to capture the height at regularly spaced intervals. All proving grounds have this data for a variety of their courses; similar data can be collected in the field. Newer techniques involve replacing the rod-and-stadia-level with a profilometer to collect data. Typically, terrain height is captured every 75, 150, or 300 mm depending on the level of detail desired.



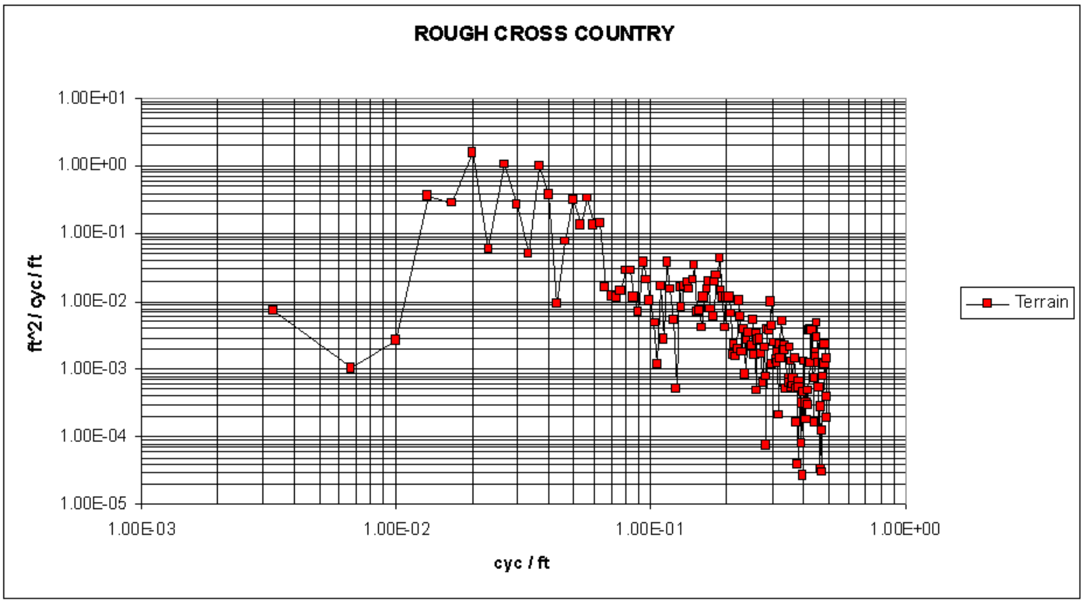


Figure 2.4 - Terrain surface spectra.

This data is filtered to detrend it. The U.S. Army uses a high-pass filter to remove all wavelengths longer than 60 feet (~18 m) from the data. This is a standard procedure, because the longer wavelengths do not affect vehicle dynamics, but only affect power requirements for propulsion. After detrending, the power spectral density, or wave number spectrum, is computed for subsequent dynamic analysis.

2.3.1.2 Air

Characterisation of the atmospheric turbulence, which is the principle external excitation of aircraft, has been a long-standing study. Formal velocity distributions, defined by Von Karman or Dryden models, describe the distribution of air velocity in all 3 axes as a function of either frequency or wave number. These standard distributions are scaled with altitude to capture altitude induced characteristics and are scaled by rms. velocity to illustrate turbulence intensity.

While the aforementioned velocity distributions define gust spectra, they do not clearly identify the large gusts, or “air pockets” well known to most air travellers. These separate gusts are specified uniquely in design documents and aircraft certification criteria to ensure that the vehicle can withstand their effects.

An excellent summary of this material can be found in the AGARD Structures and Materials Panel Symposium Proceedings “The Flight of Flexible Aircraft in Turbulence” [AGARD (1986)].

To illustrate the specifications for military aircraft, the remainder of this section is abstracted from the MIL standard for air vehicle disturbances, MIL – 8785C.

Atmospheric disturbances are defined in two atmospheric disturbance models: a low altitude model and a medium/high-altitude model. These define the atmospheric disturbances to be used to show compliance with the requirements of the specification at altitudes below 2000 ft AGL and above 2000 ft AGL, respectively. The low altitude model consists of four parts: steady wind, random turbulence, discrete gusts, and wind shear. The medium/high-altitude model consists of two parts: random turbulence and discrete gusts. According to scale and magnitude, disturbances are further classified for the purpose of determining compliance as common, uncommon, or extraordinary.

Steady wind is the mean wind speed; in the absence of wind shear, the mean wind speed and direction are constant. Different orientations of the mean wind relative to the runway should be considered for takeoff and landing regimes of flight which require more precise control of aircraft position, as should orientations relative to the aircraft flight path for other phases of flight.

Random turbulence components have Gaussian (normal) distributions. Turbulence spectra can be either the von Karman form or the Dryden form. Scale lengths and intensities for the low altitude model are continuous functions of altitude. Scales and intensities for the medium/high-altitude model are based on the assumption that the turbulence (above 2,000 ft) is isotropic. Root-mean-square turbulence intensities for the medium/high-altitude model are shown on figure 2.5 as functions of altitude and probability of exceedance; these magnitudes apply to all axes. The dashed lines, labeled according to probability of exceedance, are based on MIL-A-8861A and MIL-F-9490D. The solid lines indicate a simplified approximation to this model for the purpose of determining compliance to the specification. A minimum rms magnitude of 3 ft/sec is specified at all altitudes in order to assure that aircraft handling will be evaluated in the presence of some disturbance. Typical low altitude measured turbulence spectra are shown on figure 2.6.

The discrete gust model may be used for any of the three gust velocity components. Gusts may be used singly or in combinations. They are generally of (1–cosine) form, although step functions or linear ramps may also be used. Several length (or time) scales should be used, chosen so that the gust is tuned to the natural frequencies of the air vehicle and its flight control system (higher frequency structural modes may be excepted). Alternatively, specific discrete gust data that have been extracted from gusts encountered during air vehicle flight tests can be used.

The wind vector shear is defined by a change in direction of the mean wind speed over a given height change. A range of values for the initial wind orientation and the initial altitude for onset of the shear should be considered. Shear magnitude is defined from the mean wind profile as a function of altitude.

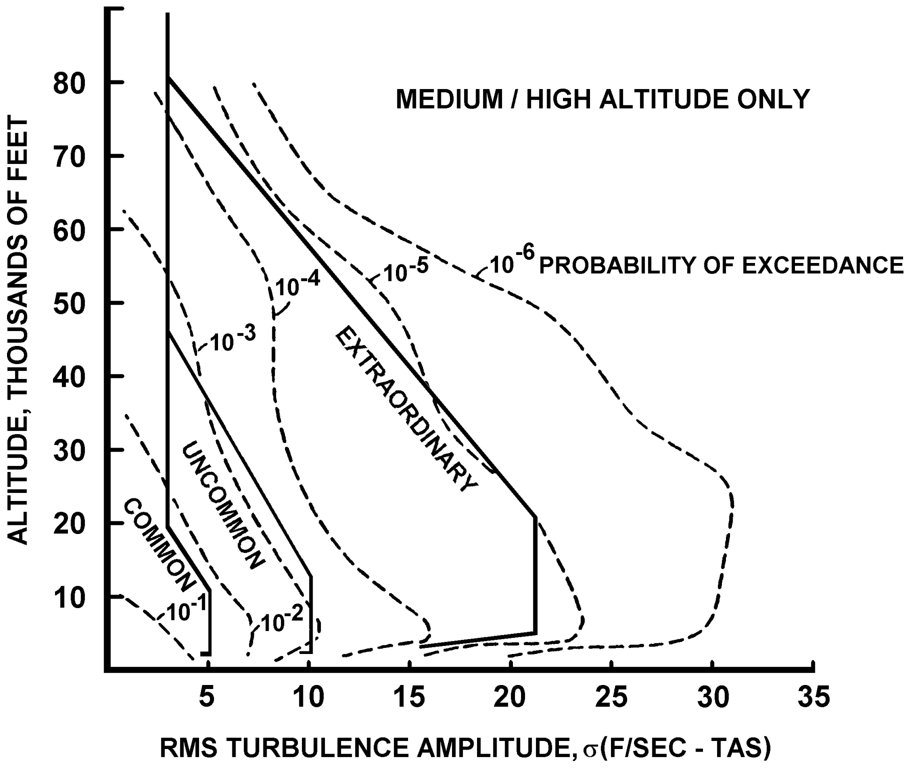
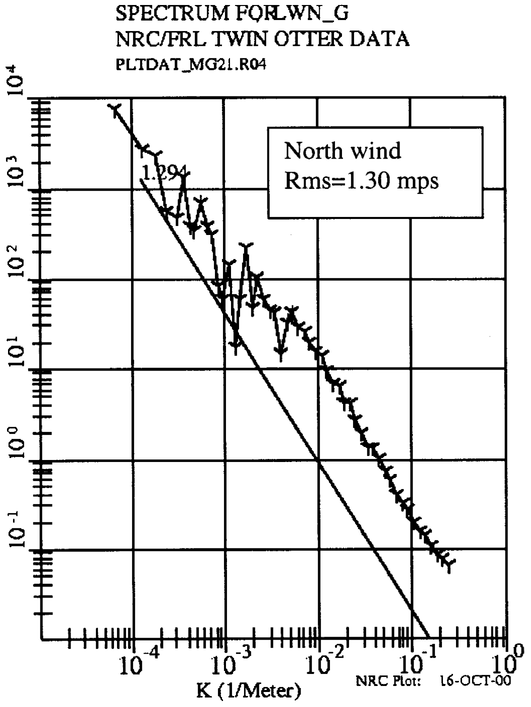
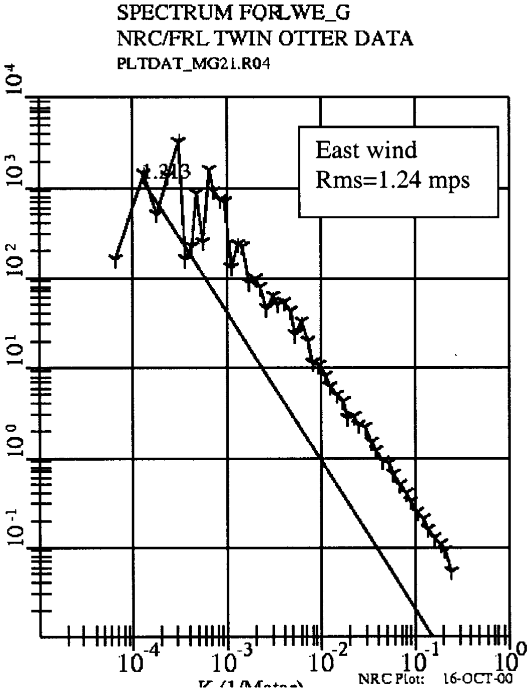


Figure 2.5 - Turbulence intensities and probabilities of exceedance.





Twin Otter data : Mackenzie Tundra

Altitude 150 ft

16 km run length

x-axis k = inverse of wavelength in meters

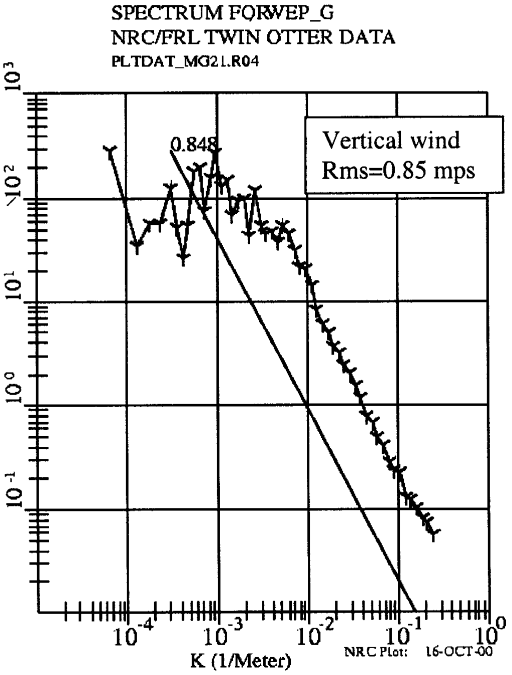


Figure 2.6 - Three-component (north/east/vertical) low altitude measured air turbulence measured spectra.

2.3.1.3 Sea

The current NATO seastate definition is based solely on significant wave height (mean of the 1/3 highest waves), Table 2.2.

Table 2.2 - Seastate characteristics.

NATO		**Most Probable**	
		North Atlantic	
Sea State	**Significant Wave Height (m)**	**Wave Period (s)**	**Wavelength (m)**
0	0	—	—
1	0 – 0.1	—	—
2	0.1 – 0.5	—	—
3	0.5 – 1.25	5.0	40
4	1.25 – 2.5	7.5	90
5	2.5 – 4	9.7	150
6	4 – 6	12.4	240
7	6 – 9	15.0	350
8	9 – 14	16.4	420
9	>14	—	—

Wave directional and frequency characteristics and the probability of wave height occurrence are determined by geographic location and time of year. Wave height is strongly correlated with wind speed and wind history. The table includes some representative values of wave period and wavelength for seastates 3 to 8. The most probable wave periods coincide with the time scales of naval surface vessels in Figure 2.3, and the wavelengths are of the same order as their hull lengths, resulting in strong coupling between seastate and ship motion. In high seastates, surface vessels are also subject to additional transient loads from hull slamming and green water impact on the superstructure.

Wave spectra data, formerly gathered by weatherships, is now mostly obtained from instrumented wavebuoys. Historical wave data is catalogued by region, time of year, and other parameters for environmental forecasting. For dynamic analysis, actual spectra are usually approximated by idealised spectra, Figure 2.7.

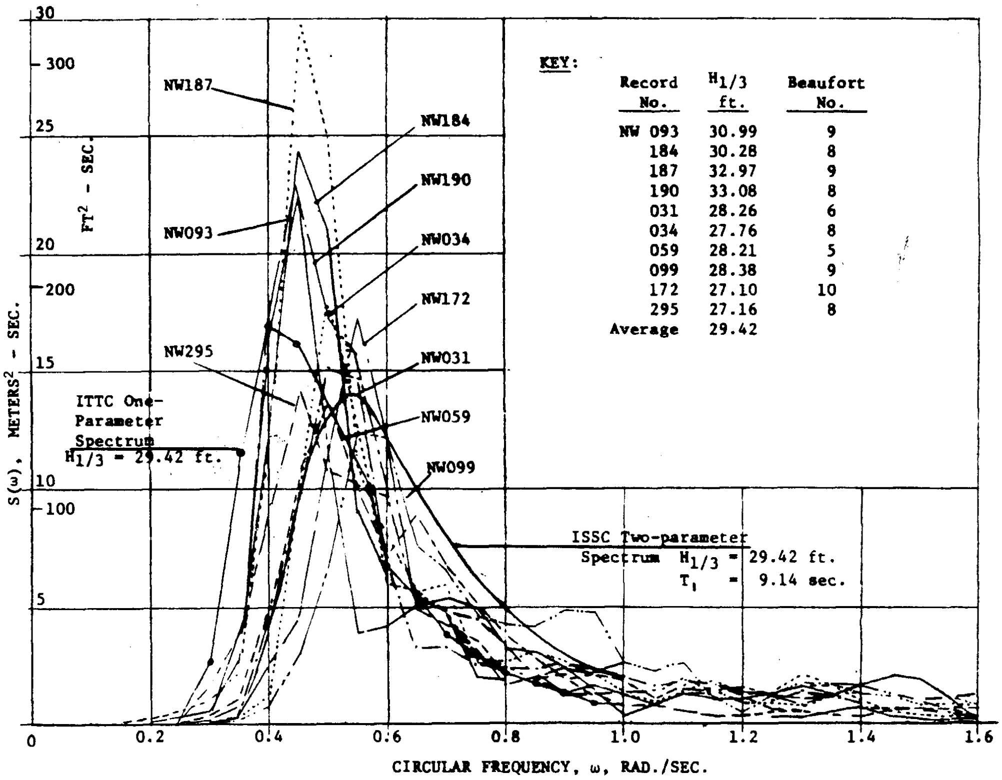


Figure 2.7 - Long crested wave spectra records for a significant wave height of about 10 m, with one- and two-parameter idealised spectra. (From Lewis 1988).

2.3.2 Multi-Vehicle and Infrastructure Interactions

Multi-vehicle interactions (which are generally aerodynamic or hydrodynamic) occur between vehicles in close proximity. While this has been already discussed to some extent in sections 2.2.3 and 2.2.4 regarding coupled and towed systems, there are many other operational situations in which this happens. A related class of problems, especially so far as modelling is concerned, is that of operation in proximity to some fixed infrastructure, e.g., ship manoeuvring in confined waters, or a helicopter landing and takeoff in the wake of a ship hangar. In most cases, the modelling and simulation of all these conditions are primarily related to crew training and safety issues although sometimes the interaction can define vehicle dynamic or control limits.

Land:	High speed convoy operation, articulated vehicles, railway trains, vehicles passing in the same or opposite directions, passage through tunnels or under bridges.
Air:	In-flight refuelling, stores release, formation flight, landing and takeoff, “Wing in Ground Effect” vehicles (WIG), helicopter slung loads.
Sea:	Replenishment at sea, manoeuvring in shallow or confined waters, subsurface weapon launch.
Space:	Capsule/parachute systems, vehicle docking manoeuvres.

An indirect interaction — where the element of proximity is not necessarily present — occurs when land vehicles destroy the road or cross-country surface conditions over which other vehicles have to travel. A front wheel may deform and compress the surface encountered by a rear wheel. Analogously, persistent shed vortices are a problem for aircraft landing and takeoff, and ship wakes can be a hazard for smaller craft, even at large separations.

2.3.3 Environment Properties

The properties of the land environment vary considerably, often over a very short time scale, and must be properly accounted for. Thus, soil or other surface, modelling is a significant component of simulating tire or track dynamics at the interface. Surface properties may vary naturally, or may be modified by the vehicle itself, or by other vehicles, as noted above.

For military vehicles, operating on roads as well as in terrain, the following environmental factors are important for mobility:

- Terrain slope, lateral and longitudinal – up to 60% for military vehicles, see section 2.4.
- Tire-road friction coefficient, as a limiting factor for transmission of traction forces, braking forces, and lateral tire forces. Friction depends on speed when the road is wet. Table 2.3 presents typical values of the tire-road friction coefficient.

Table 2.3 - Tire-Road friction coefficient

Ground	$f_{x\ max}$	
	Dry	Wet
Concrete	(0.95 – 1.2)	(0.5 – 0.9) *
Asphalt	(0.8 – 1.2)	(0.7 – 1.0) *
Ice	(0.15 – 0.25) *	
* dependent on speed and on tire profile		

- Soil strength parameters, which enter into the calculation of rolling resistance and traction on soft ground, are required for simulating off-road operation. Water content (hence weather, and weather history) is a decisive factor. Simulations must take account of a wide variation in local values of these parameters. Table 2.4 demonstrates their variability.

Table 2.4 - Typical soil strength parameters

		P pressure-sinkage z			max. shear-tension	
		$p = \left(\frac{k_c}{B} + k_\varphi\right) \cdot z^n$			$\tau_{max} = c + p \cdot \tan \varphi$	
Dimensions	Vol %	N/cm^{n+1}	N/cm^{n+2}	-	N/cm^2	0
Characteristic Value	WC	k_c	$k\varphi$	N	c	φ
Sand	0 %					
	17,3	19,7	11,5	0,58	0,5	22,8
Loam dry	10,3	54	22,2	0,73	1,2	40
Loam wet	35,7	7,7	6,5	0,34	0,8	17
Clay humid	38,8	23,6	18,0	0,16	2,9	12,9
Clay wet	44,4	12,3	7,0	0,15	1,1	5,3

B: diameter of plate or width of tire z: sinkage p: normal pressure

As the tables above suggest, simulation models must consider the influence of weather on water content and on soil strength parameters.

For the air environment, temperature and pressure are implicit in the altitude and dynamic pressure that are critical to aircraft characteristics. In addition, takeoff and landing are normally critical at higher altitudes and hotter temperatures. Air and atmospheric models may have to be incorporated in simulations. Space vehicle dynamics may be susceptible to non-uniform solar heating.

2.3.4 Cross-Environment Interactions

There are a number of problems that involve interaction between vehicles or systems operating in different environments; these include:

Land/Sea:	Transport (roll on and off or crane lift).
Land/Air:	Transport, LAPES and other airborne cargo delivery operations.
Air/Sea:	Fixed-wing or helicopter flight deck operability.
Air/Space:	Re-entry dynamics.

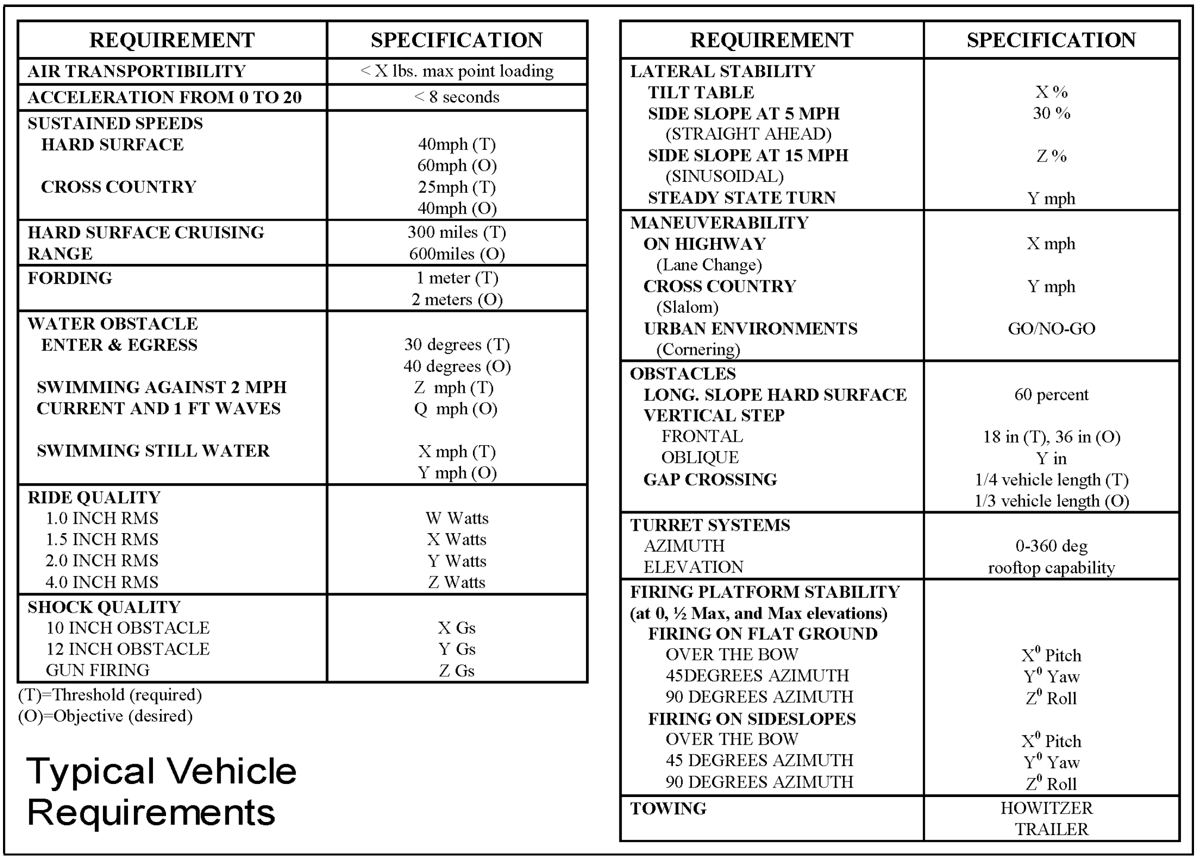
As noted for vehicles operating in the same environment, the modelling and simulation of these conditions are frequently related to crew training and safety issues.

2.4 MISSION ENVELOPES

The mission envelope of a vehicle may be based on performance requirements, on estimated performance, or on empirical observation. Manoeuvring evaluation involves comparison of requirements and observed performance, but dynamic estimates are key in design and development. An estimated mission envelope encapsulates information generated by modelling and simulation, while defining the major parameters for those activities. A number of examples follow.

2.4.1 Land

Figure 2.8 is a representative listing of land vehicle performance requirements; specifically, the characteristics that quantify requirements for on and off road dynamic stability and manoeuvrability, mobility, ride, and shock quality. While not a graphical envelope, this format conveys comparative performance information for a variety of operational events.



REQUIREMENT	SPECIFICATION
AIR TRANSPORTIBILITY	< X lbs. max point loading
ACCELERATION FROM 0 TO 20	< 8 seconds
SUSTAINED SPEEDS	
HARD SURFACE	40mph (T) 60mph (O)
CROSS COUNTRY	25mph (T) 40mph (O)
HARD SURFACE CRUISING RANGE	300 miles (T) 600miles (O)
FORDING	1 meter (T) 2 meters (O)
WATER OBSTACLE	
ENTER & EGRESS	30 degrees (T) 40 degrees (O)
SWIMMING AGAINST 2 MPH CURRENT AND 1 FT WAVES	Z mph (T) Q mph (O)
SWIMMING STILL WATER	X mph (T) Y mph (O)
RIDE QUALITY	
1.0 INCH RMS	W Watts
1.5 INCH RMS	X Watts
2.0 INCH RMS	Y Watts
4.0 INCH RMS	Z Watts
SHOCK QUALITY	
10 INCH OBSTACLE	X Gs
12 INCH OBSTACLE	Y Gs
GUN FIRING	Z Gs

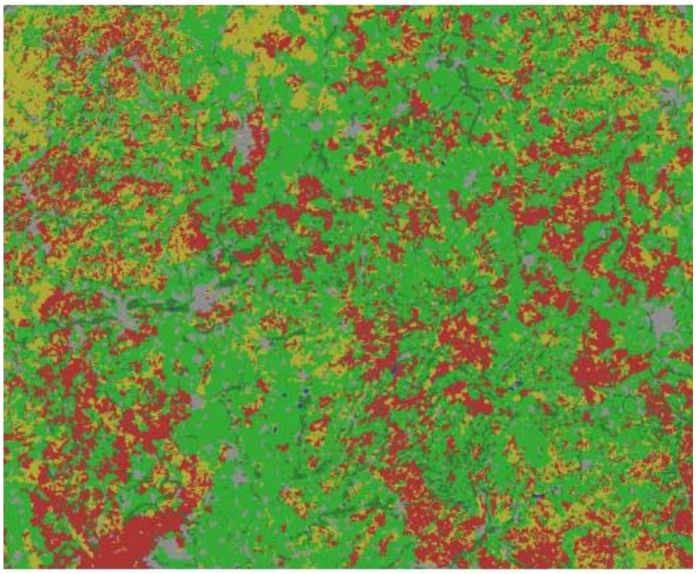
(T)=Threshold (required)
(O)=Objective (desired)

Typical Vehicle Requirements

REQUIREMENT	SPECIFICATION
LATERAL STABILITY	
TILT TABLE	X %
SIDE SLOPE AT 5 MPH (STRAIGHT AHEAD)	30 %
SIDE SLOPE AT 15 MPH (SINUSOIDAL)	Z %
STEADY STATE TURN	Y mph
MANEUVERABILITY	
ON HIGHWAY (Lane Change)	X mph
CROSS COUNTRY (Slalom)	Y mph
URBAN ENVIRONMENTS (Cornering)	GO/NO-GO
OBSTACLES	
LONG. SLOPE HARD SURFACE	60 percent
VERTICAL STEP	
FRONTAL	18 in (T), 36 in (O)
OBLIQUE	Y in
GAP CROSSING	1/4 vehicle length (T) 1/3 vehicle length (O)
TURRET SYSTEMS	
AZIMUTH	0-360 deg
ELEVATION	rooftop capability
FIRING PLATFORM STABILITY (at 0, ½ Max, and Max elevations)	
FIRING ON FLAT GROUND	
OVER THE BOW	X^0 Pitch
45DEGREES AZIMUTH	Y^0 Yaw
90 DEGREES AZIMUTH	Z^0 Roll
FIRING ON SIDESLOPES	
OVER THE BOW	X^0 Pitch
45 DEGREES AZIMUTH	Y^0 Yaw
90 DEGREES AZIMUTH	Z^0 Roll
TOWING	HOWITZER TRAILER

Figure 2.8 - Typical land vehicle requirements.

For mobility-specific vehicle system performance issues, the NATO Reference Mobility Model (NRMM), developed in the early 1970s, combines many mobility-related vehicle technologies into one comprehensive package. It is designed to predict the physically constrained terrain/vehicle interaction for on and off road operations and provides NATO members with a standard reference for mobility performance evaluations. Once mobility predictions are made for an area of interest and seasonal conditions such as wet, dry, winter etc. are factored in, colour-coded maps of speed and mobility allow the visualisation of areas of the terrain where mobility is possible, figure 2.9. General paths of interest are selected from the predicted mobility corridors, figure 2.10, and these paths are then used to determine best mobility routes, figure 2.11. NRMM is also integrated into other models to provide the mobility predictions for several tactical, analytical and war-gaming simulations.



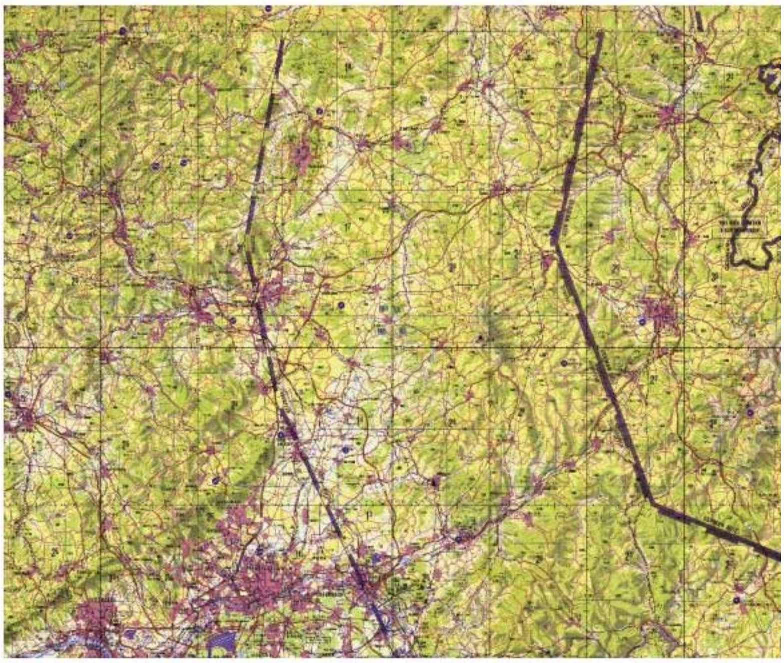
This is the mobility prediction used to select the best mobility route. Red is No-Go, Yellow is Difficult-Go and Green is Go.

Figure 2.9 - Area wide mobility predictions.

Map Scale 1:250,000

The lines represent selected routes for NRMM to find the best path using a 7 KM wide search corridor.

Figure 2.10 – NRMM Best Path Routes.



This is a close up of the resultant corridor chosen by NRMM to choose possible mobility routes.

Figure 2.11 - Close up of a resultant corridor from the mobility predictions.

The increased capacity of computers has enabled to develop new simulation methods that allow a detailed description of the complex system consisting of the vehicle, the driver and the environment. One of the most sophisticated examples for wheeled vehicles in on and off road conditions is the IKK simulation Program ORSIS (On and Off Road Systems Interactive Simulation) which is further described in Appendix I.

2.4.2 Air

Helicopter flight envelope limits may be in terms of allowable limits (strength of components) and/or achievable limits (performance). For example, a traditional load factor-velocity envelope is shown in figure 2.12(a). The limiting phenomena vary as one moves around the edges of this envelope. The upper acceleration limit is usually associated with the maximum aerodynamic or structural capability of the rotor and airframe. The maximum speed limitation is usually established by which specified manoeuvre margins exist. Figure 2.12(b) shows a typical sideslip versus airspeed limit; for this envelope there is a steady limit and a transient limit. Also, there are limits on engine/transmission torque, and main rotor rpm over- and under-speed. Some of these limits are time dependent. That is, transient torque exceedances are acceptable for short periods. This has fatigue life implications. In addition to the allowable and achievable “hard” limits, there are also recommended “avoid” regions within the helicopter flight envelope. A classic example is shown in the height-velocity diagram, figure 2.12(c). In this case, the regions to avoid are determined through the evaluation of engine failure cases. If the vehicle is outside the height-velocity avoid areas when an engine failure occurs, it is expected that the pilot can make a successful flyaway or autorotation to a touchdown. If the vehicle is inside one of the height-velocity avoid areas when an engine failure occurs, the result may be catastrophic.

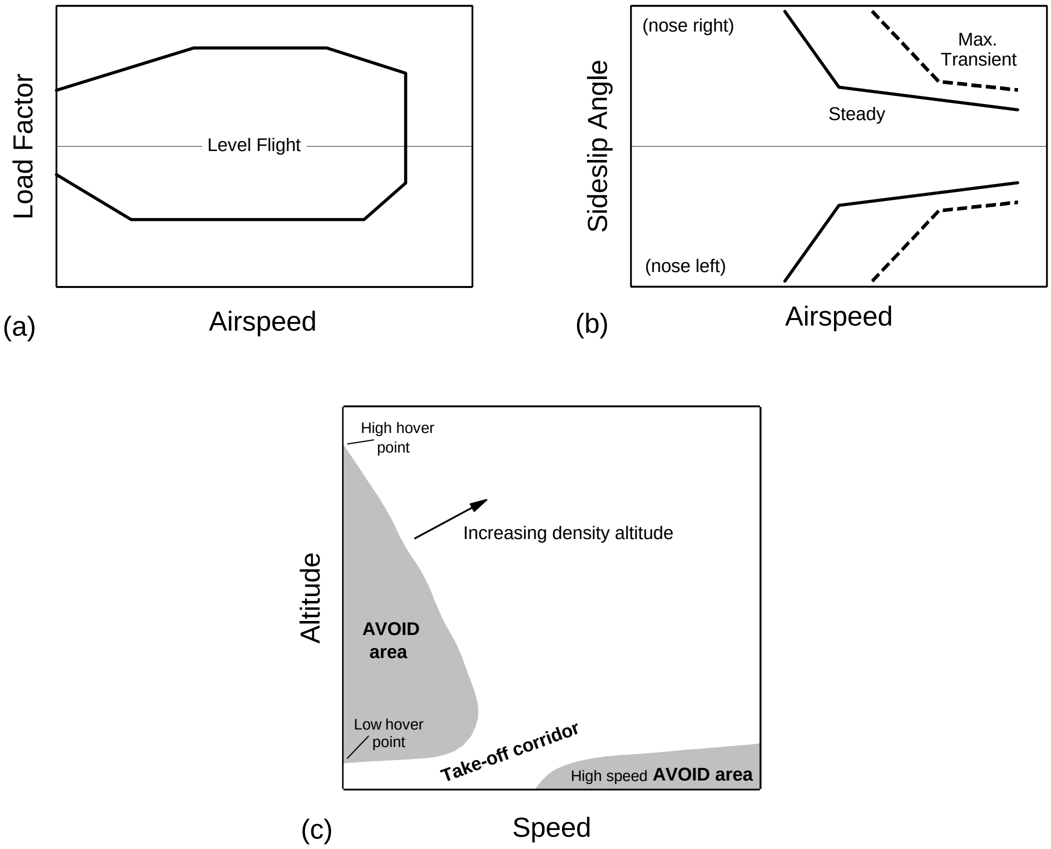


Figure 2.12 - Helicopter flight envelope limits: (a) acceleration, (b) sideslip angle, and (c) height-velocity limits.

Fixed-wing aircraft have similar load factor-velocity and engine performance envelopes. In the flying quality specifications, they are defined as Operational and Service Flight Envelopes. In the Operational Flight Envelope (OFE), the aircraft is expected to be able to perform all mission requirements with Level 1 handling qualities (satisfactory without improvement), without any failures. The Service Flight Envelope is required to include the OFE and define aircraft limits where handling qualities can be Level 2 (deficiencies warrant improvement)(again with no failures). For aircraft failure states, handling qualities are allowed to degrade in both envelopes subject to limits on the probability of encountering a failure.

Other limits for aircraft include a margin from stall, and less-well defined limits such as departure from controlled flight.

2.4.3 Sea

Figure 2.13 comprises polar plots of warship operability in a seaway for two different operational scenarios (both for transit). Typically, numerous such scenarios are specified. The condition that limits operability is indicated for each heading angle; note that the design limit is not achieved at every heading in the lower plot. These conditions range from ship/system integrity limits (i.e., propeller emergence, slamming) to crew performance limits (i.e., vertical accelerations and tipping MIIs).

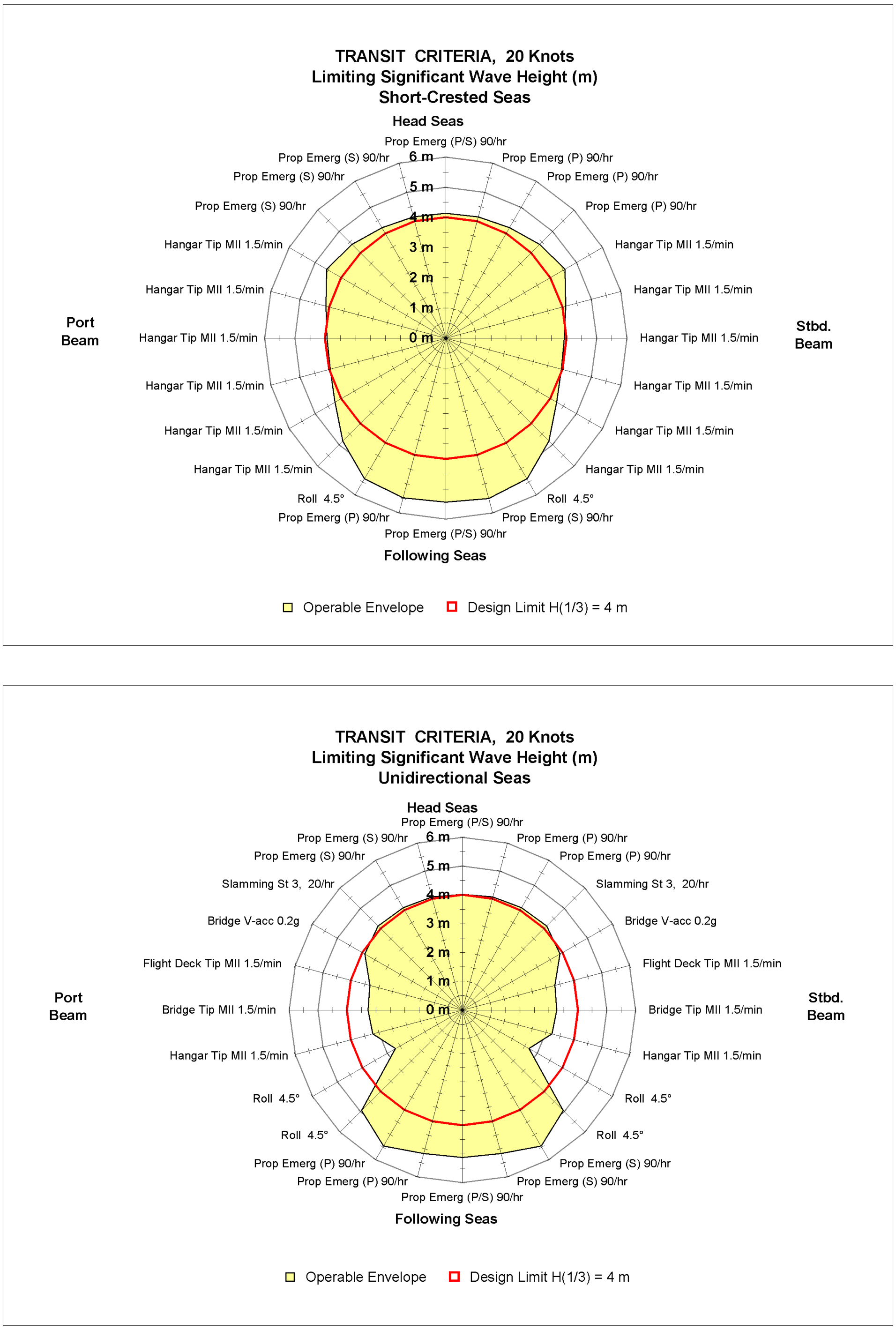


Figure 2.13 - Warship operability in a seaway. (From NATO STANAG 4154, 1997)

A generic landing/takeoff envelope for helicopter–ship operation is given in Figure 2.14. The asymmetry in the envelope is due to the asymmetric performance capabilities of typical helicopter tail rotors. This plot is based on relative wind on the flight deck, and does not take account of ship motions that would further reduce the envelope.

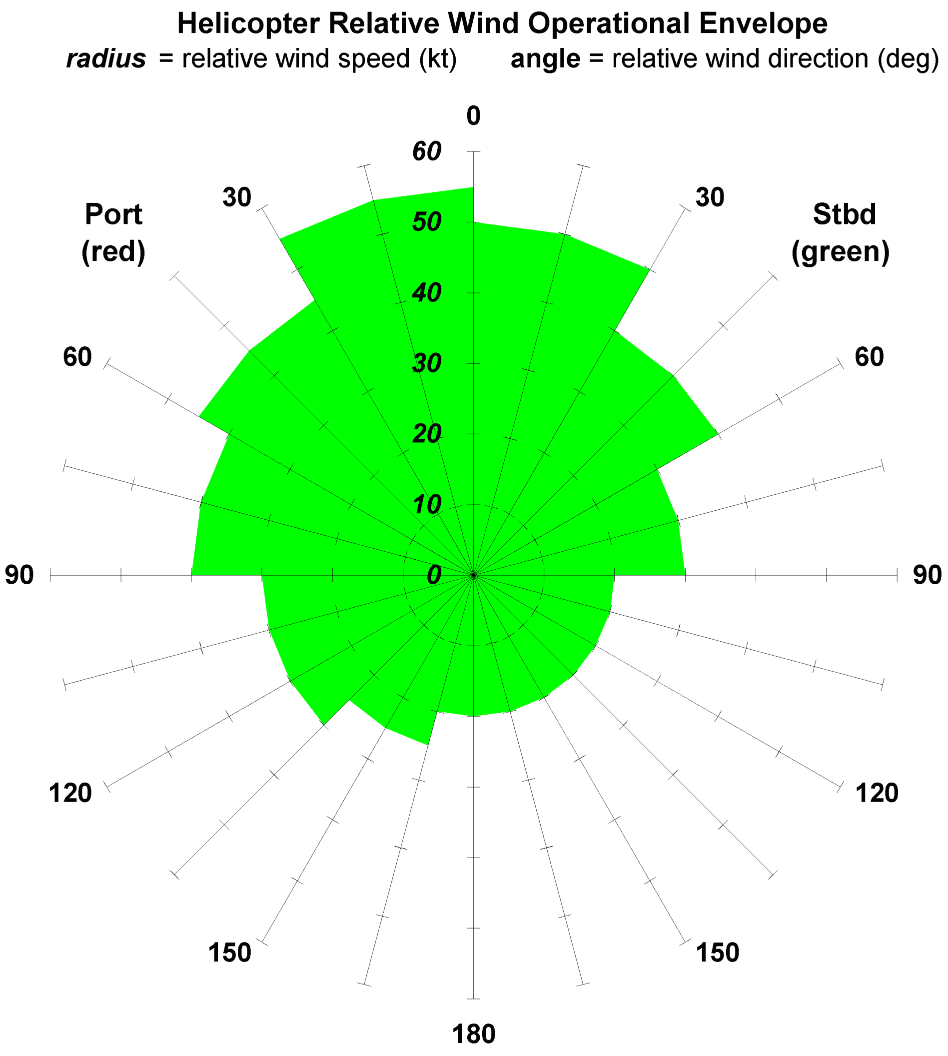
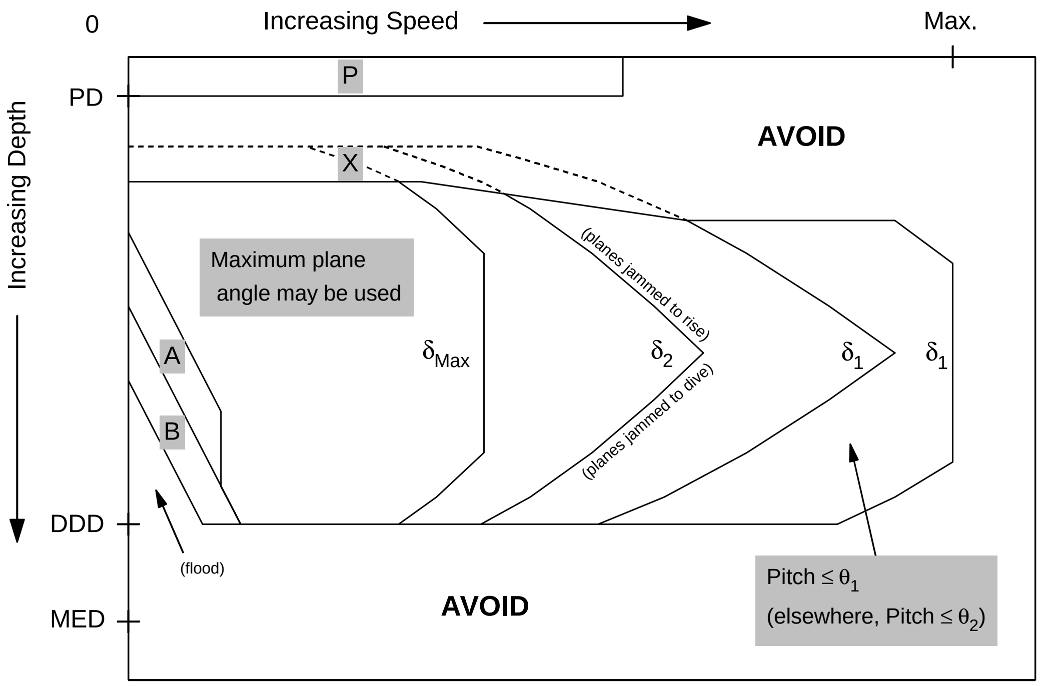


Figure 2.14 - Landing/takeoff envelope for helo–ship operation.

Submarine manoeuvring in the vertical plane is restricted to a safe operating envelope within the manoeuvring limitation diagram (MLD). A schematic example is shown in Figure 2.15. Unrestricted manoeuvring can take place within the innermost envelope. The boundaries are expanded if limits are placed on pitch angle and sternplane deflections. The lower boundary will be raised when the available depth is less than the maximum excursion depth (MED). The MLD may exist in different versions for different (e.g., peacetime or wartime) safety rules.

There is a notable analogy with the air environment: the MLD is in many respects an inverted version of the aircraft height-velocity limit diagram, figure 2.12(c).



Speed:	Max.	maximum submerged speed
Depth:	PD	periscope depth
	DDD	deep diving depth
	MED	maximum excursion depth
Operating Regions:	A, B	avoid in shallow charted depth (safety margins)
	P	transit between periscope depth and surface only
	X	avoid where deep draft surface vessels operate
Parameters:	δ_i, $i = 1, 2, \ldots$, Max	magnitude of plane deflection, $\delta_1 < \delta_2 < \delta_{Max}$
	θ_i, $i = 1, 2, \ldots$	magnitude of pitch angle, $\theta_1 < \theta_2$

Figure 2.15 - Schematic Submarine Manoeuvring Limitation Diagram.

2.5 SUBSYSTEM-RELATED DYNAMICS ISSUES

As greater accuracy and therefore detail in a simulation model is required, various subsystem characteristics must be incorporated. A number of those most significant for vehicle dynamics, such as land vehicle suspension systems, have been mentioned previously in this chapter. This section summarises other important examples from each environment.

2.5.1 Sensors, Vehicle and Environmental

Land: Attitudes, rates, and accelerations. GPS, vehicle speed, engine and transmission parameters, traction control settings, payload configuration.

Air: Attitudes, rates, and accelerations. GPS, inertial platform, airspeed vector, pressure altitude, radar, control surface deflection and engine settings, fuel state. In missiles, dynamic control will be coupled with target acquisition and tracking (these functions may be aboard the firing, or another, platform).

Sea: GPS, inertial platform, speed log, radar, control surface and propulsion settings, fuel state, sinkage, trim. Underwater and semisubmersible vehicles also have sonar for collision avoidance and under-ice operation, and sensors for pressure depth, ballast configuration, and density or salinity. In torpedoes, dynamic control will be coupled with target acquisition and tracking (in wire-guided torpedoes, these functions may be aboard the firing submarine).

Space: Star detection sensors, inertial platform, GPS.

2.5.2 Control Effectors and Systems

Land: Wheels or tracks, active and passive suspension components, differential traction, central tire inflation systems, traction control systems. Backhoes, bulldozer blades, etc. Legs (e.g., walking vehicles).

Air: Deflected aerodynamic surfaces, vectored thrust, circulation and boundary layer modification (e.g. riblets) and control. Ballast and buoyancy control in aerostatic vehicles. Passive control, WIG Vehicles, etc.

Sea: Deflected or flapped hydrodynamic surfaces, vectored thrust, circulation control, boundary layer control and modification, e.g., heat, polymer injection. Ballast and buoyancy control in underwater vehicles, ballast control and flume (anti-roll) tanks in surface vehicles. Passive control: surface-piercing hydrofoils, etc.

Space: Gyro stabilisation and attitude control, attitude thrusters.

Many aspects of control systems and technologies (Chapter 4), including fly-by-wire (and fly-by-light) have found application in both manned and unmanned vehicles in all environments. There are, however, differences in philosophy. For example, the longitudinal instability (or at least reduced stability) now considered for improving the manoeuvrability of military aircraft is usually incorporated into the design with multiple levels of control redundancy but no “manual backup”. In marine applications (and civil aircraft) a minimal manual “get-home” capability is generally still required. In the latter case, control bifurcation, etc., will have to be accurately modelled in a simulation. There are also some environment-unique problems. For example, buoyant ascent of an underwater vehicle may have multiple stable states. This situation may be controlled in an unmanned vehicle, but may not be in a submarine, which does not generally have a capability for roll control.

2.5.3 Propulsion

The major components of a vehicle propulsion system are (one or more of) a power source, a motor, a transmission, and a propulsor; examples are given in Table 2.5. In cases such as an aircraft turbofan engine, these components are effectively integrated. In others, e.g., a marine diesel/electric or nuclear/steam turbine plant driving a propeller, the components of the propulsion system each have significant characteristics, and must be modelled individually. For land vehicles, the propulsors are frequently also the control effectors; this dual role occurs with the use of vectored thrust in some air and sea vehicles.

In addition to the characteristics of the hardware, the control dynamics of propulsion systems, including operator response, have a significant impact on vehicle manoeuvring.

Table 2.5 - Propulsion Summary

	Land	**Air**	**Sea**	**Space**
Power	Distillate fuels Gas, e.g., propane Battery Fuel cell	Distillate fuels Solid fuel Solar cell	Distillate fuels Oxidiser (for AIP) Battery Fuel cell Chemical reaction Nuclear	Distillate fuel LH Oxidiser Cold Gas RCS Solid Fuel Chemical reaction Fuel cell Nuclear
Motor	Piston engine Gas turbine Electric motor	Piston engine Turboprop Turbojet Fan jet Rocket Electric motor	Piston engine Gas turbine Steam turbine Electric motor	Rocket
Transmission	Mechanical Electric Hydraulic	Integrated Direct/mechanical	Direct/mechanical Electric	Integrated
Propulsor	Wheels, tires Tracks	Integrated: vectored Propeller: variable pitch, vectored Rotor: CCP	Propeller: fixed-pitch, CPP, shrouded, vectored, cyclic pitch/ vertical axis Pumpjet Airscrew	Integrated

2.6 ADDITIONAL PARAMETERS

2.6.1 Short Term Parameters

There are additional parameters in defining the vehicle dynamics that reflect changing conditions or vehicle configuration. Some of these changes can be classified as short term, i.e., those that typically occur in the course of a mission, and which must therefore be represented by parameters that vary during the simulation. The parameters are generally similar in the different environments:

Land: Variation in fuel, crewmember and ordinance loads, variability (that may be very large) in cargo loading configuration, casualty configurations, weather-dependent terrain conditions.
Air: Variation in fuel, stores, weapons, and ordinance load, casualty configurations, configuration changes such as flap and landing gear extension and retraction and also in tilt-rotor and swing-wing aircraft.
Sea: Variation in fuel, stores, and weapons load, variation in cargo and other deployable elements, casualty configurations.

Complete change of environment (and in some cases a major configuration conversion) occurs in the course of a mission for amphibious assault vehicles, e.g., wheeled/tracked swimmers and ACVs. Less drastic, but still significant, are the effects of a change in properties of the local environment — i.e., soil and surface properties on land.

Switching fuel type in multifuel power plants may have to be modelled, as may change of plant in combined power plant systems, e.g., marine CODOG.

2.6.2 Long Term Parameters

Long term additional parameters are those that characterise a particular vehicle configuration and that remain unchanged over at least the duration of a mission. They can be temporary or permanent — for example, service life modifications. The latter may effectively define the parameters of a new vehicle that is then considered a variant, or subclass, of the baseline design. (And indeed, from the point of view of modelling, would be treated as a new design.) These modifications typically result in altered vehicle mass characteristics and operational capabilities. Examples are:

Land:	Semipermanent and permanent vehicle conversion for mission requirements, e.g., a truck used as a troop or cargo carrier , wrecker, fuel hauler, ambulance, etc.
Air:	Fuselage stretch, structural life extension (mid-life upgrades), additional external sensors, stores, etc.
Sea:	Surface vessel draft and trim changes with weight growth, additional or updated topside sensors; a submarine hull plug for AIP, etc.

2.7 OTHER ISSUES, UNIQUE FACTORS, AND COMMON PROBLEMS

2.7.1 Unmanned vehicles

Unmanned vehicles draw on the technology of (typically, larger) manned vehicles but present some unique problems. The mathematical descriptions of the dynamics of corresponding manned vehicles may not be adequate due to scaling effects (for example, because of fluid dynamic scale effects). Even with a similar role and payload, unmanned vehicles weigh less because of reduced armour and other human-support requirements, and manoeuvres are not constrained by human-factor limits on rates and acceleration. Exploiting these characteristics puts increased demands on the control system.

Unmanned vehicles currently in-service include:

Land:	Robot vehicles for surveillance, mine clearance, and combat assessment.
Air:	UAVs – micro- and small aircraft for surveillance, combat assessment, and target designation, missiles, smart bombs.
Sea:	Torpedoes, ROVs and UUVs for reconnaissance survey, mine clearance, cable laying, and hull inspection.

Weapons such as smart bombs, missiles, and torpedoes should also be considered in this category.

2.7.2 Unique Factors and Problems

The following factors and problems are essentially unique to a specific environment. As with the previous category, there is likely to be limited scope for the application of technologies from other environments.

Land:	Low contact load requirements for mine avoidance, weather, terrain (soil properties, lateral forces etc.), road surface and traction characteristics. Power pickup for high speed electric rail – pantograph and catenary dynamics.
Air:	Supersonic and hypersonic flight dynamics, icing, ballistic weapons and projectiles, rotary-wing aircraft, VSTOL, flutter and buffet.

Sea:	Cavitation, ventilation, free surface effects, added mass, (subsurface) variable inertial properties (e.g., ballast tank blowing), spray drag, surface ice interactions.
Space:	Highly flexible vehicles, gravitational variation, heating rate (re-entry vehicles).

2.7.3 Common Dynamics Problems

From the discussion presented in this chapter, it is clear that while the dynamics of land, air, sea and space vehicles are considerably different in many aspects, there are areas of mutual interest. These areas are promising candidates for cross-environmental collaboration. They could very well be the focus of RTO technical events that bring together experts from the various environments to initiate common approaches and solutions. Several such areas are listed below:

- Amphibious and swimming vehicles – there is a clear interaction between maritime and land technologies in this area. However, it may be that too few of these vehicles are built to have forged a permanent connection between these communities in the past.

- Structure-rigid body coupling – most air vehicles now consider this coupling and its effects on the control system early in the design process, but flight tests often reveal a less than satisfactory treatment of the issue. Flexibility of the tank gun barrel and drive train are major land concerns. Helicopter rotors are aeroelastic elements, and the airframe may deform significantly with a slung load. Ship deformation in a seaway is a significant fatigue and structural strength issue, but is generally at frequencies well above those of interest for manoeuvring and seakeeping. Propeller shaft whipping, however, may adversely affect engine control.

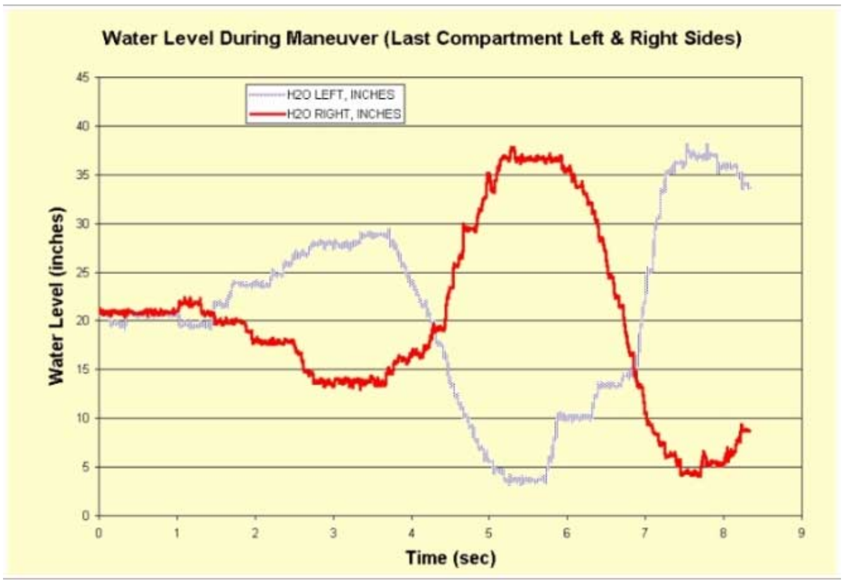


Figure 2.16 - Tanker truck slosh measurements. (From WVU (1998).)

- Liquid slosh dynamics – most vehicles have problems when partially filled containers of liquid contribute to free-surface instability or impart transient forces on the vehicle. Figure 2.16 shows slosh measurements made on a tanker truck during a lane change. In the marine environment, slosh is of benefit in the case of passively or actively tuned flume tanks sometimes used for roll stabilisation. For space vehicles and weapon systems, slosh may impact the stability of launch dynamics.

- In each environment, signature control introduces operational modes or constraints that impact the vehicle dynamics. Although specific applications are unique, the underlying technologies, e.g., thermal radiation or acoustic transmission control, are common, and may suggest analogous solutions.

- Actuator limitations – i.e., in acceleration, rate, or displacement. These may create dynamics and control problems such as loss of performance, instability, limit cycling, pilot-induced oscillations, etc. Control system design will be required to address these difficulties: for example, anti-windup systems.

- Non-linear dynamics – each type of vehicle has areas of the envelope that are far from the linear realm. Modelling may be environment-specific, but methods of numerical solution in a time simulation are universal. Potential problem areas cited in this chapter include complex coupled systems, singularities, stiff/nonstiff equation sets, discontinuities, etc.

- The impact dynamic problems of land vehicles and crash survivability (required for helicopters, etc.) may be related through considerations of structural energy absorption. Work on underwater shock and blast, weapon firing blast and weapon recoil technology in all environments may have significant similarities.

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Chapter 3 – Vehicle Modelling and System Identification

This chapter presents an overview of the modelling techniques currently in use for land, air, sea and space vehicles and describes the various system identification processes available to discern appropriate model structures and to precisely define the parameters contained within specific models. It focuses on the concepts and approaches employed in this domain, rather than trying to define the exact state-of-the-art in each subject addressed. Similarities and differences between environments are indicated where obvious; however, a definitive assessment of where commonalties in technology exist, and can be exploited, is reserved for the concluding discussion in Chapter 6.

3.1 OVERVIEW OF MODELLING TECHNIQUES

Over the last decades modelling and simulation of vehicle dynamics has become an integrated part of the various stages of vehicle design, development, certification, production and optimisation process.

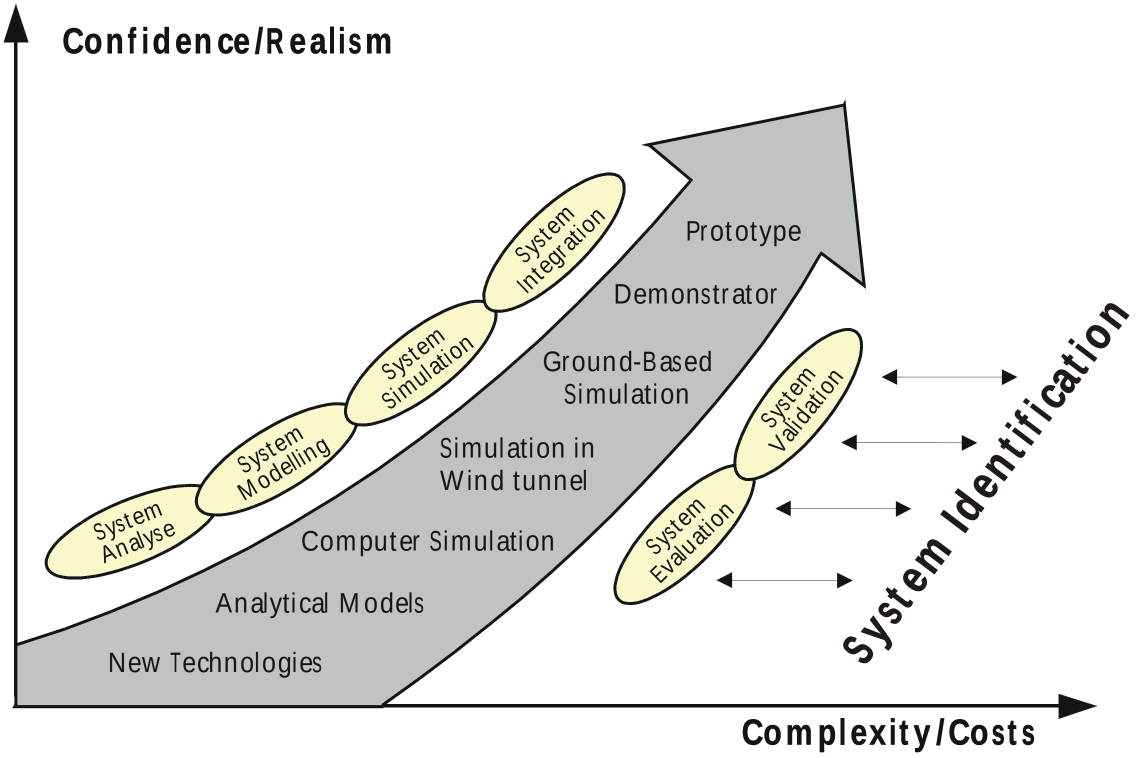

Fig. 3.1 - System identification as a supporting method

As depicted in Fig. 3.1, modelling and system identification are techniques employed throughout the complete development process, particularly for aircraft and helicopters. Complexity and effort increase rapidly as the process moves closer to the real-world. Modelling techniques can be broadly classified into three groups, namely:

- explicit modelling, which may loosely be called white-box modelling, using first principles of physics or empirical knowledge,
- implicit modelling, like transfer functions or neural networks, often called black-box modelling, and
- a combination of the explicit modelling and black-box methods, which may be termed grey-box modelling.

The choice of modelling technique is often dictated by the application at hand. In general, explicit modelling techniques involve models based on physical interpretation of the phenomenon being investigated and are highly suitable for dynamic systems. Such models can be described in the time-domain using state space techniques or by transfer function models in the frequency domain. The parameters appearing in these models can either be estimated from experimental data using system identification techniques or can be specified using a-priori knowledge. Nevertheless, this method can be very time-consuming if complex non-linear effects have to be described.

Black-box techniques, e.g. neural-networks, provide capabilities to model any degree of non-linearity and are thus suitable for phenomena which are difficult to formulate mathematically. They result in a model structure and corresponding parameters (weights) which cannot be interpreted in terms of physical quantities, hence the name black-box modelling. The main objective of such models is to describe the macroscopic output-input-behaviour of the system, not to understand the underlying system structure. Experimental data must be used to determine the model and its parameters. Due to the lack of a physically derived structure, black-box models often exhibit poor extrapolation properties and special care should be taken when using such model for predicting behaviour that was not covered by the test data that the model was derived from.

The third approach of grey-box modelling combines the features of the two aforementioned methods, e.g. using a mostly physically motivated model structure and incorporating black box models for hard to describe phenomena to improve the fit of the model behaviour to the experimental data.

In practice, the simulation of real dynamic systems is usually based mostly on grey-box modelling. Dynamic systems can normally be described using Newtonian mechanics. Unknown phenomena, such as aerodynamic effects, can be modelled using a generic approach or parametric models. Since the model parameters cannot be measured directly, parameter estimation methods have to be used. This measurement-based approach using system identification techniques is, of course, restricted to modelling existing vehicles; for the early phase of vehicle design, only prediction-oriented modelling using empirical and theoretical knowledge can be used.

3.2 MODELLING CHARACTERISTICS

3.2.1 General Aspects

The purpose of this section is to introduce and compare suitable model structures for vehicle modelling and system identification. A model structure is a set or family of candidate models that are considered appropriate for describing the dynamics of a vehicle or system. Although linear model structures have several advantages as a starting point for modelling and control system development purposes, non-linear mappings will be necessary for high fidelity simulations. Linearity aside, some other characteristics of mathematical models are:

- stable / unstable
- continuous / discontinuous
- deterministic / stochastic
- parametric / non-parametric

Typical model structures are algebraic functions, time series models, transfer functions, ordinary and partial differential equation systems, universal approximation schemes (e.g. neural networks and fuzzy systems), and knowledge based systems

Another aspect which requires some consideration is model parameterisation, e.g. the number of unknown parameters and the choice of constant or time-dependent parameters. For white-box modelling, parameterisation can be based on physical insight, but in the black-box approach, parameterisation is not related physically to the system and may convey very little information to the user.

Modern vehicles are becoming increasingly complex and highly integrated systems. The optimal modelling technique for each component can be quite different. Thus, hybridisation of different modelling concepts and multidimensional simulation is used more and more often.

3.2.2 Land Vehicles

Wheeled and tracked vehicles are usually considered as multi-body systems with many subsystems and interconnection elements. For structural modelling and modal analysis, finite element (FE) methods are often employed to evaluate component stiffness, strength and durability. The study of the structural responses under high impact loads is another challenging aspect of land vehicle modelling. System identification methods are used for updating and validating the structural discretized system, e.g. the FE-model. Coupling of multi-body simulation and finite element analysis with parameter identification (PID) techniques leads to complex models with significant non-linearities.

There are several commercial packages available for land vehicle modelling, including both white-box and black box formulations. Many modellers use in-house developed code, which is not commercially available. The most critical and difficult part of a land vehicle model is the interface of the vehicle and the ground, whether that is through a tire or a track on the vehicle, and whether the ground is soil, paved road, or a rail. These interactions are the most significant force inputs to the model, and the interfaces are not as well understood as their counterparts in other domains. An important issue regarding ground vehicle modelling is that there is no standard for the data file format, thereby, making it difficult to convert a model from one software package into one compatible with another.

For wheel-rail interactions the contact area and velocity must be accurately predicted. Additionally, slip and normal force at each contact point must be modelled to study the potential for loss of traction. Further modelling complexities arise from situations involving vehicle payloads that may move in reaction to vehicle dynamics and the requirement to accurately model highly aggressive manoeuvring as well as the modelling of vehicles following the failures of physical components or systems.

Additionally, real-time models are important for hardware-in-the-loop and “man as operator” uses. Such simulations cannot achieve their desired purpose unless the model can respond in real time to inputs arising from the hardware or the operator. Complexities in the land vehicle modelling process, including closed kinematic loops and large impulse-like forces from the ground, make real-time modelling of land vehicles difficult when compared to other domains. The significant challenge is to get models that respond in real time to external events without sacrificing validity of results from the simulation.

Some of the current technical activities in the modelling of land vehicles are

- the application of frequency domain PID techniques
- the application of time domain methods to determine non-linear models, e.g. for passive and active vehicle suspension systems

3.2.3 Air Vehicles

For flight dynamics purposes, aircraft are usually modelled as rigid body systems with six degrees-of-freedom. Four or more control effectors (elevator, aileron, and rudder deflection and thrust setting) are normally taken into account. Secondary control devices (flaps, landing gear, etc.) may also have to be considered. The modelling of aero-elastic effects, like flutter and structural coupling may be important for high performance or large flexible aircraft. For total system simulation, the subsystem interactions have to be quantified and a hybridization of different modelling concepts may be used.

The determination of stability and control derivatives from flight data to verify wind tunnel aerodynamic coefficient estimates has been a standard application of system identification for several years. More recently, PID has also been successfully used to determine data bases covering the whole operational envelope of an aircraft for use in piloted (fixed- or moving-base) simulators [Jategaonkar *et al. (1994)*, Jategaonkar *et al.*(1997)]. The modelling of aircraft at high angles-of-attack requires the understanding and modeling of non-stationary aerodynamic effects such as dynamic stall [Fischenberg (1995)]. The modelling of the strong coupling between some physical phenomena and aircraft motion (turbulence, aeroelastics, ground effects, etc.) are important research topics. Extended system identification techniques have been developed for application to unstable aircraft [Jategaonkar *et al*. (1994)]. Recently, system identification has been applied to several sophisticated non-standard configurations..

Rotorcraft are typically modelled as high-order systems with fuselage dynamics, rotor dynamics, propulsion and transmission dynamics. Most of these models have significant non-linearities at low speed, at high angular rates and during special circumstances such as blade stall and auto-rotative flight. Strong coupling between the longitudinal and latera-directional motion as well as between rotor and fuselage occurs under most operating conditions. Model structure determination is required for non-linear coefficients, coupling terms, and a number of significant rotor modes.

In general, parameter estimation of rotorcraft requires the simultaneous estimation of a large number of parameters. Therefore, usually multiple manoeuvres have to be evaluated together to determine all parameters. Furthermore, system instabilities might induce further problems.

3.2.4 Sea Vehicles

From the point of view of manoeuvring, a marine vehicle, whether surface or subsurface, is considered to be a rigid body moving in an earth-fixed reference frame. In the most general case, six degrees of freedom are retained, even for surface vessels, resulting in six equations of motion that are conventionally expressed in Euler co-ordinates. Marine vehicle hydrodynamics are notably non-linear, even for routine manoeuvres.

Time history effects can be important, and some attempt is usually made to incorporate them. The Standard Submarine Equations of Motion [Feldman (1979)] use time delays such as represented by t_o in the following equation to account for these effects:

$$\boxed{\text{Vehicle predicted state}(t+\Delta t) = F\,(\text{vehicle kinematic history state}(t-t_o),\ \text{vehicle state}(t))}$$

In more elaborate "rational flow" models, time history effects are given a physical basis by tracking the downstream propagation of shed vortices, etc. For surface ship simulations, time history effects tend to be less important, and modelling them may be less straightforward; however, it is becoming more common to model them if the effort is justified.

The virtual mass effect, that is an increase in the effective vehicle mass representing a portion of the mass of water surrounding the vehicle, must be taken into account for sea vehicles. The equations of motion are augmented by additional equations for the response of control surface and propulsion subsystems, and for the vehicle manoeuvring and control autopilots.

The primary problem for efficient and accurate system identification is establishing a model for hydrodynamic forces and moments as well as for unknown terms in the additional system equations; other terms can be adequately estimated. A complication for surface vessels is that the added masses and moments of inertia, as well as the damping, are frequency–dependent, and thus may require considerable modelling effort. Numerical models can be of any type or degree of complexity. For manoeuvring (time) simulations, a physics-based coefficient model is commonly used, although the nonlinearities will be incompletely represented; more complex models are required for extreme manoeuvres, capsize, etc. Physics-based models are often linear in the hydrodynamic coefficients, which simplifies the task of parameter estimation. These are generally cast in a similar form for both sub-surface and surface vessels although they differ significantly in some details (e.g. compare Feldman (1979), and Inoue *et al.* (1981)) because of the free surface.

Hydrodynamic coefficients can be deduced directly from fully-scale trials or model experiments using system identification, from Computational Fluid Dynamics (CFD), or can be estimated from a component breakdown of the vehicle using semi-empirical methods [Bohlmann (1991), Inoue *et al* (1981b)]. The latter approach is routinely used for vehicle subsystems such as propulsion. The complexity of both hydrodynamic and subsystem models may be significantly increased in order to simulate critical manoeuvres, e.g., for establishing a safe operating envelope. Itard (1999) notes that up to 900 equations have been used in modelling a nuclear propulsion plant for submarine emergency recovery studies.

Common Aspects

The linearized equations of motion for stability analysis [Mackay (2001)], have much in common with air vehicles.

- Classical wedge impact theory, developed for application to seaplanes landing on water [von Karman, (1929),Wagner (1932)], has historically been the basis for estimating the slamming forces on a ship in a seaway. Nowadays, FE-based techniques are more likely to be used.
- Similar problems relative to experiments on scaled models
- Numbers of state and control variables are similar.

Differences

- Equations of motions with the buoyancy and added mass terms
- Different test techniques (inputs, duration, etc.)
    - time scales are significantly longer for ships and submarines
    - absence of direct and efficient control in roll for submarines (but desirable only in extreme manoeuvres)
- Cavitation and free surface effects influence, often adversely, sea vehicle performance
- Ventilation – near surface aeration – may adversely affect propeller efficiency in light loading condition, and is significant for hydrofoils.
- Seakeeping is typically modelled in the frequency domain for operability assessments; this is possible because ship motions are reasonably linear up to moderate sea states. For manoeuvring, on the other hand, non-linear modelling in the time domain is required.

3.2.5 Space Vehicles

Tactical missile model identification is similar to aircraft, but important differences have to be considered due to short flight time. Since each vehicle can often only be used once, mathematical models must be developed from a number of vehicles, accounting for manufacturing differences. Launch vehicles are characterised by large engine thrust and high drag. Complex aerodynamic models are necessary due to the fact that the vehicle traverses a large mach number region in a short time and because of the special thrust characteristics. Due to the high gains employed in the autopilots which are required for stabilized flight, aerodynamic force and moment derivatives are often exceptionally difficult to determine.

Re-entry bodies

- Complex dynamics and aerodynamics for complete flight regime
- Non-linear control effectiveness

Space Structures

Modelling of structural and mechanical behaviour of large space structures is a very challenging problem, with finite element methods being the preferred technique. Numerous difficulties are caused by the intense environments, and in particular, the effects of solar heating. Given the exceptional focus on structural weight, the structures are quite flexible by earth-borne standards, leading to additional challenges concerned with this flexibility and how it interacts with structural control.

Common aspects with air and space vehicles are:
- Modelling concepts (aerodynamic modelling)
- Similar equations of motion
- Order of bandwidth characterisation (dynamics)
- Aeroelastic effects
- Same methods for analysis (time and frequency domain)

3.3 INTRODUCTION TO SYSTEM IDENTIFICATION

System identification is a multi-disciplinary methodology of increasing importance for the modelling of vehicles. Basically, it provides an approach to develop mathematical models that represent the vehicle dynamics, before, during, or after the design is complete.

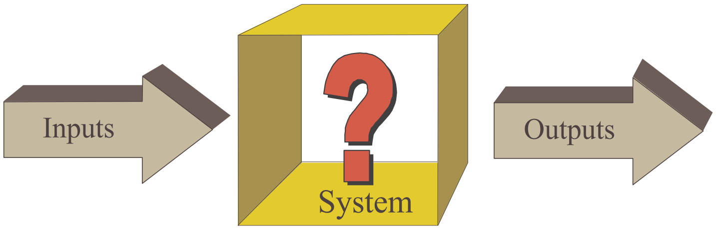

Fig. 3.2 - System Identification Approach

During the last 30 years, the mathematical methods and tools have reached a high level of sophistication and maturity. Applications of system identification have shown that a significant saving in test time and test cost can be achieved, while improving accuracy and reliability of estimated results.

System identification links structural mechanics, aerodynamic and hydrodynamics, flight mechanics, terra mechanics and system theory. Identification methods are applicable to a broad spectrum of platforms, including land, air, sea and space vehicles (manned and unmanned). Similar problems arise in the areas of choice of suitable excitation (manoeuvres), proper design of test instrumentation (measurements), determination of model structure (models) and the choice of identification algorithms (methods).

The main benefits and applications of modelling using system identification approach are:

- Improved understanding of the basic cause and effect of non-linear responses
- Reduced time and cost of vehicle/system testing
- Reduced cost, operational impact of design errors and reduced development risks
- Improved vehicle safety issues
- Improved system/vehicle performance
- A basis for control design, active-control-technology, etc.
- Improved predictive capability of simulators
- Support to accident investigations

Although system identification has become, more or less, a standard tool, interpretation of the results must be done carefully by trained engineers. Completely automated techniques for this purpose are rather difficult, but quite a few systematic procedures are available to ease the workload and to streamline the model development process.

3.4 THE SYSTEM IDENTIFICATION PROCEDURE

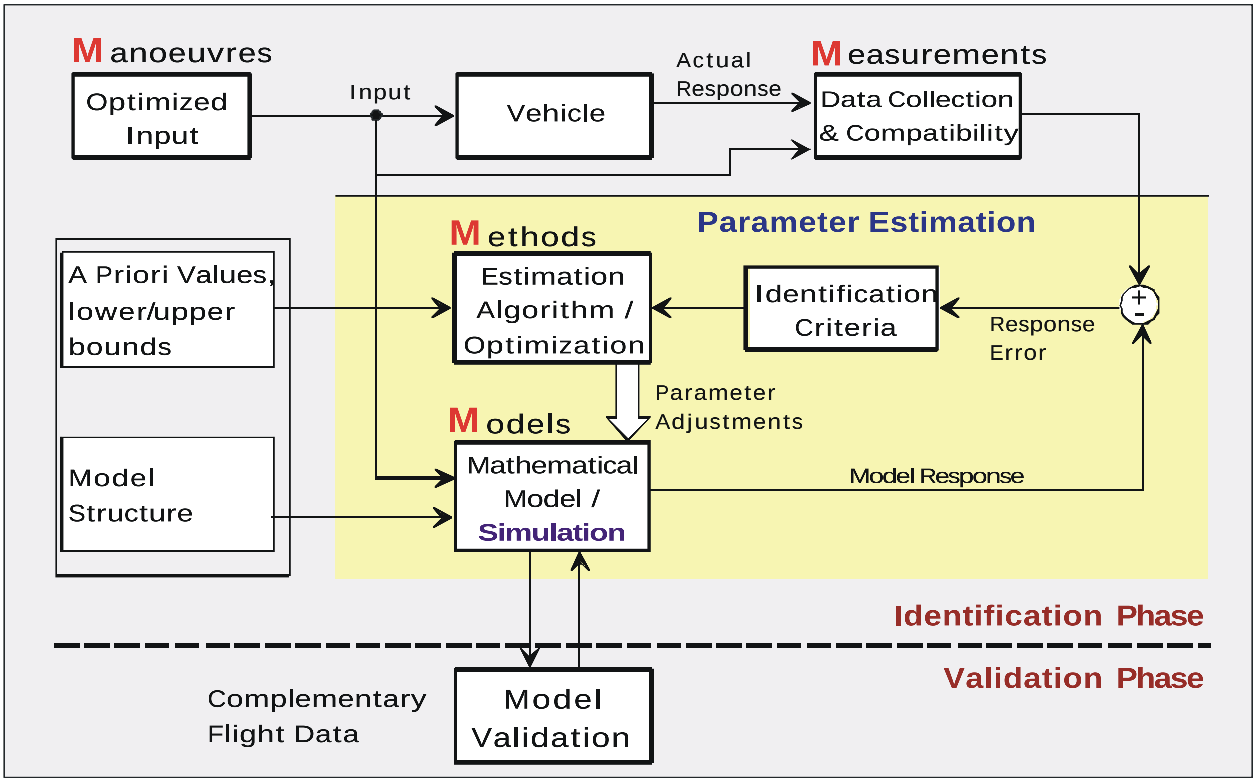

Figure 3.3 - The Quad-M basics of System Identification

The most important aspects of system identification are covered by the so-called Quad-M basics, depicted in Figure 3.3:

i) Manoeuvres – design of the experiments so that the control inputs excite all modes of the dynamic system that will be identified,
ii) Measurements –all aspects of data quality including the selection of instrumentation and filters for high precision data acquisition,
iii) Models – postulation of the appropriate model structure based on the physical understanding of the dynamic behaviour, if possible, and
iv) Methods – proper choice of time or frequency domain parameter estimation method, accounting for measurement noise as well as process noise if necessary and possibly considering a-priori information and/or parameter bounds.

Most of the above aspects are further elaborated upon in the following sections on experimental design, instrumentation, and mathematical methods.

Validation of the identified model is an integral part of system identification. In general, it is recommended that the validation be carried out on complementary data, i.e., on a set of data not used in the model estimation. This evaluates the predictive capability of the identified model, ideally over a broader range. To eliminate the tendency to subjectively evaluate the predictive capability of a given model, specified guidelines for vehicle models have been developed. For airplane simulators, these are listed in the FAA Advisory Circular 120-40C and the JAR_STD 1A [FAA (1995), JAR(1997)].

3.5 EXPERIMENTAL DESIGN FOR SYSTEM IDENTIFICATION

3.5.1 General Aspects

To collect a set of data that describes how the vehicle behaves over its entire range of operation, a specifically tailored series of experiments is usually required. Generally both open and closed loop inputs are required to completely characterise the system.

The scope of the models that can be identified is, in general, limited by the "information" contained in the data sets being analysed. Hence, proper test techniques and suitable excitation of system modes are critical to successful application of system identification methods. Manoeuvring procedures and optimised control inputs have to be selected in their spectral composition in order to excite all vehicle response modes from which model parameters are to be estimated. The following are important criteria for the design of data generating experiments:

- The operational regime of the vehicle,
- The availability of manual and/or computerised input signals,
- The type of input to be employed: stochastic, deterministic, frequency sweep, multi-step input, etc.
- The excitation required to identify the model of vehicles with embedded control augmentation.

Besides these general aspects, the choice of test manoeuvre and the design of input signals is dictated by the particular vehicle class and application.

3.5.2 Land Vehicles

In general, land vehicles are evaluated using test procedures that were developed for personal cars; however they are also used for commercial and military trucks. While sub-optimal in many respects, the tests that are used to verify the dynamic stability of land vehicles can also be used as baseline data to verify vehicle models. The three primary tests employed are:

- A steady state circular test where the vehicle is driven in turning circles to the right and left with minimum diameters of 60 meters. For each trial condition, data are taken as the vehicle is in a dynamically steady state for at least 3 seconds. The procedure is repeated with various circle diameters.
- A double lane change test as illustrated in figure 3.4. The test should be repeated with two different drivers.
- Frequency domain analysis of the vehicle response to a sinusoidal steering input.

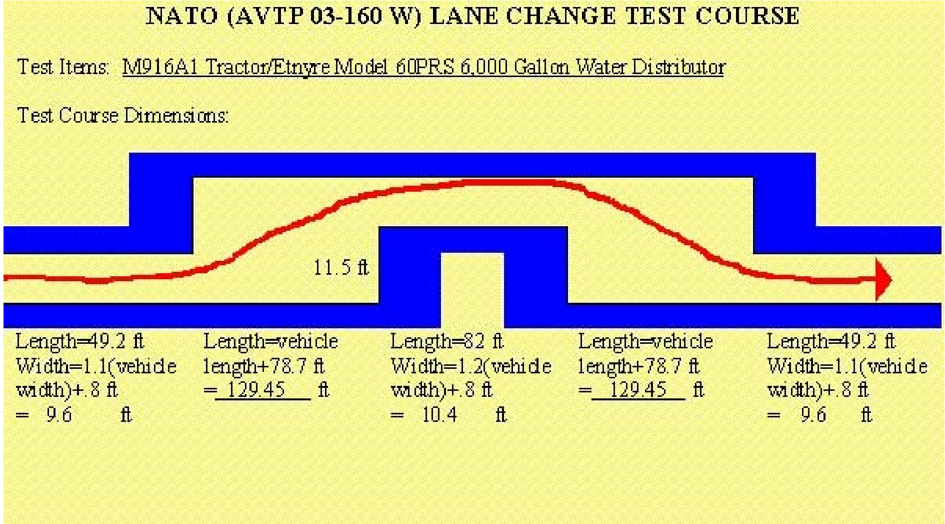

Figure 3.4 - Lane Change Test Course (from WVU (1998))

With regard to vehicle-body oscillations resulting as a response to excitation by unevenness of the road, a frequency domain analysis usually is performed for identification of the system.

The following sections describe the different performance tests that are necessary to fully quantify the cross-country mobility characteristics of off-road vehicles. These tests verify that the vehicle has a minimum level of performance as well as allowing direct mobility performance comparisons of one vehicle system to those of another. The test results are also used to validate the mobility model discussed in Chapter 2. Each test is described in terms of its underlying purpose and its general procedure.

- Soft Soil Tests. A key indication of a vehicle's cross-country mobility performance capabilities is its ability to traverse soft soil areas. Soft soil test results can be used to directly compare the mobility characteristics of different vehicles (or configurations), and it can also be used to rank a particular vehicle's capability relative to a predefined desirable level. In a typical soft soil test, a level, straight-line, homogeneous (as much as possible) test lane is marked off for the test, and then the vehicle makes passes through the test lane at a slow, steady state speed (»2 mph) in its lowest gear. The vehicle will continue to make forward and backward passes until immobilization occurs. Soil consistency data are measured in an area adjacent to the immobilization but out of the zone of disturbance. The measured soil strength is intended to represent the soil strength that is characteristic of the immobilizing pass number for the particular vehicle and terrain conditions.

- Traction Tests. Overall mobility performance is largely dependent on the amount of traction a vehicle can develop between the ground surface and its running gear. Dramatic reductions in overall mobility performance can occur with reduced traction on sand or on wet fine-grained soils, even though the mass soil strength is more than adequate to support the vehicle. Traction can be quantified in terms of the average horizontal tractive force developed at the terrain interface, and this force can be broken down into two unique quantities: (1) drawbar pull, and (2) motion resistance. The sum of these two quantities is equal to the traction. The drawbar pull - slip test data are used to establish a relationship between drawbar pull coefficient (D/W) and slip for each of the particular vehicle configurations and terrain conditions.

- Slope Climbing Tests. Frequently during movement operations, vehicles are forced to climb slopes, and these slopes can be barriers preventing the successful completion of a mission particularly in cross-country travel. Slope climbing ability is directly related to traction performance capability, and a good approximation for the maximum percent grade that a vehicle can climb is the drawbar pull coefficient that it can obtain on a level surface with the same terrain/climatic conditions characteristic of the slope (this approximation doesn't work as well for loose sands. In a typical slope climbing test, natural cross-country slope courses are located that are at least a couple of vehicle lengths long and have the desired soil type and consistency. The slope courses may be slightly improved to remove vegetation and provide a desired slope grade. Several slope courses will be utilized for each terrain condition so that a few slope grades below the maximum slope negotiable and at least one slope grade above the maximum slope negotiable are available with a grade increment among the slopes of about 2%.

- Ride Quality Tests. Ride quality is an important factor related to the overall mobility performance of a vehicle system. The weakest link in a vehicle system when negotiating natural rough terrain is typically the human operator. Human tolerance to whole body vibration limits the overall ability of a vehicle system to successfully accomplish its mission. Ride quality can be quantified by using the absorbed power criterion. Absorbed power is derived from acceleration measurements, and it is representative of the rate at which a typical human body absorbs vibrational energy. Studies have indicated that humans may often subject themselves to 10 - 20 watts of absorbed power for short periods of time, but they usually will not subject themselves to more than 6 watts for very long time intervals. Therefore, 6 watts of absorbed power has been consistently used in ride quality studies as the standard human tolerance limit for vertically induced vibrations. The absorbed power level observed by a particular vehicle system is primarily a function of the vehicle speed and the terrain roughness characterized by the root-mean squared (rms.) elevation (in.). Ride quality assessments are typically conducted by developing ride performance relations for vehicle speed at 6 watts of average vertical absorbed power as a function of roughness. These relations can be used to directly compare the mobility characteristics of different vehicles (or configurations) and/or rank a particular vehicle's capability relative to predefined desirable levels.

- Shock Quality Tests. An important part of a vehicle's overall mobility performance capabilities is its ability to negotiate abrupt discrete obstacles without imposing excessive discomfort on the vehicle occupants and without causing physical damage to the system components. Logs, boulders, small ditches, rice paddy dikes, etc. are all examples of discrete obstacles that are frequently encountered in cross-country travel. Shock performance can be quantified for a particular vehicle system by evaluating the maximum peak acceleration (peak-g's) under the driver's seat for various size obstacles at several speeds. Many shock performance studies have been conducted, and a criterion of 2.5 g's vertical acceleration under the driver's seat has become the standard for acceptable shock limits. These studies also demonstrated that obstacle height is an acceptable first-order descriptor for characterizing the discrete obstacles. Shock performance assessments are typically conducted by developing obstacle performance relations for vehicle speed at 2.5 g's of peak vertical acceleration as a function of obstacle height.

- Traverse Tests. Typical mission roles for military vehicle systems generally require travel from one point to another via roads, trails, or off-road cross-country terrain. Such travel requires negotiating slopes, obstacles or linear features, travel in wooded terrains requiring vehicle maneuver, travel on rough sections of terrain where speeds are controlled by natural terrain surface roughness, and periods of acceleration and deceleration, all in various kinds of soils or on various road surfaces. The vehicle type, its mission, the tactical situation, the quality of the existing road net, and the terrain/climatic conditions all interplay. A traverse test is a single, fairly realistic analogy to an operational mission which essentially assesses the overall mobility performance quantified in terms of speed for a particular vehicle system by integrating the effects of many of the unique mobility performance characteristics such as traction performance, ride dynamics performance, slope climbing performance, etc. Performance summaries from a traverse test, primarily speed made good over the traverse course, can be used to directly compare the mobility characteristics of different vehicles (or configurations) and/or rank a particular vehicle's capability relative to predefined desirable levels.

3.5.3 Air Vehicles

One of the reasons why system identification has been extremely popular for air vehicles is its potential to generate all the data necessary to fully describe the vehicle dynamics based on a few, relatively simple to perform, manoeuvres. Even so, it is necessary to optimise the test procedures to reduce costly flight time and to ensure that all aspects of safety are covered. Multi-step inputs are widely used to excite particular modes of the dynamic motion. Figure 3.5 shows the frequency content of various multi-step manoeuvres that have become common for system identification purposes.

Combining different manoeuvres leads to shorter test time and significantly more information in the data. One example is superimposing an acceleration/deceleration manoeuvre (covering a wide range of speed and angle-of-attack combinations) with simultaneous multi-step inputs in different controls to excite aircraft motion.

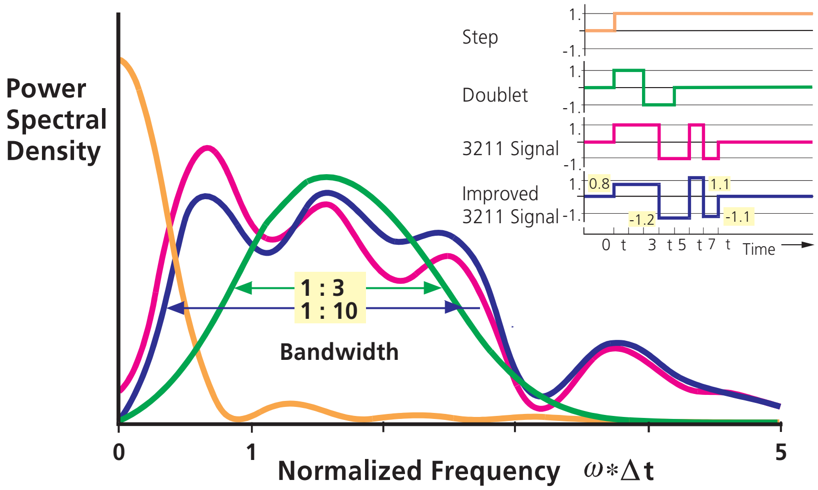

Fig 3.5 - Comparison of input signals

An aspect that requires some consideration is the way to reliably generate input signals. On-board computers have been employed to assist in this area.

For highly augmented aircraft, the control laws often lead to high correlation of input and state signals, hindering the parameter estimation process. Since state feedback is employed in the control system, it is necessary to use specialised test techniques, like single surface excitation, to improve the information content and thus reduce the ambiguities present in the final model solution [Weiss *et al.* (1996)].

For parameter identification in the frequency-domain, chirp and sweep signals are often employed since they provide a consistent excitation over the frequency range of interest. With respect to experimental costs and the reduction of vehicle testing time, these inputs are highly effective.

3.5.4 Sea Vehicles

Experimental data on ship and submarine dynamics is gathered at both model scale and full scale at different stages of design and development. However, developmental testing is done with models, and full-scale testing is used for problem solving and acceptance because economics do not permit building a prototype, unlike in the development of land and air vehicles. Although system identification and advanced methods of analysis are well established for sea vehicles [Abkowitz (1980), Haddara *et al.* (1995)], new experimental design and specialised test facilities have been slower in gaining acceptance.

A new ship design that departs significantly from existing vessels with well-documented manoeuvring characteristics is invariably subject to model testing early in the design process. As in aircraft model testing, fluid-dynamic scaling laws must be observed in order to apply or extrapolate the data to full scale, and this requires maintaining the ratios of various hydrodynamic forces. In the marine environment the principal ones are:

- Reynolds number: the ratio of inertia and viscous forces – typically sets a minimum model speed for viscous flow to be represented satisfactorily. (There is usually a large difference in overall Reynolds number between model and full scale, and there may be difficulty in achieving a critical Reynolds number, e.g., on control surfaces.)
- Froude number: the ratio of fluid inertia and gravitational forces – relates model and full scale speed for surface vessel testing; must be achieved.
- Cavitation number: the ratio of available static pressure and flow dynamic pressure – may be significant for propeller performance; must be achieved in a cavitation test.

There are others (e.g., Weber number, Strouhal number) that may result in difficulty testing very small models. Where representing the free surface is not required, wind-based test facilities may be used, but Mach number must be low enough that the flow is effectively incompressible everywhere. Since it is rarely possible to get more than one of these numbers correct for the same test conditions, multiple experiments, sometimes in different facilities, are required to fully characterise marine vehicle hydrodynamics.

The classic techniques for ship testing at model scale employ captive models at constant incidence in a towing tank or constant turning rate on a rotating arm. Surface ship models may be allowed freedom in the vertical plane to take up their own sinkage and trim, but this requires that the model have the correct inertial properties. The speed of surface ship models is almost invariably determined by Froude number scaling. The same is not the case for underwater vehicles, except for tests targeted at near-surface conditions. A more common criterion for underwater vehicles is to maximise Reynolds number so that the flow is attached on the appendages and control surfaces. For both surface and subsurface models, it is common practice to apply transition strips. Other test requirements may include modelling appendages such as rudders, fins, skegs, and bilge keels, and having propellers operating at the correct advance ratio. Testing is done in waves with both captive and free models in order to establish motion transfer functions (RAOs – Response Amplitude Operators) for sea-keeping simulation.

Dynamic testing is conducted with the model undergoing forced lateral or vertical plane motions to determine added masses, damping, and some other derivatives; for surface models these are invariably frequency-dependant. Routine dynamic testing was introduced with the Planar Motion Mechanism (PMM) [Goodman (1960)] in the late 1950s. The PMM imparts harmonic oscillations to the model. Vertical PMMs for subsurface vehicles are, with few exceptions, low amplitude devices for obtaining linear hydrodynamic coefficients; horizontal PMMs are more often large amplitude.

A new generation of test apparatus is represented by the Marine Dynamic Test Facility [Williams *et al.* (2000)] illustrated in figures 3.6 and 3.7. This device imparts large amplitude and high rate arbitrary motions to a subsurface or surface model in up to six degrees of freedom. To take maximum advantage of its capabilities requires new approaches to experimental design, and extensive use of SI techniques. The model contains a 6-DOF balance to measure total forces and moments; the control appendages may also be instrumented. An internal propulsion dynamometer is used for propulsion experiments, requiring the model to be supported by an alternative twin-strut arrangement.

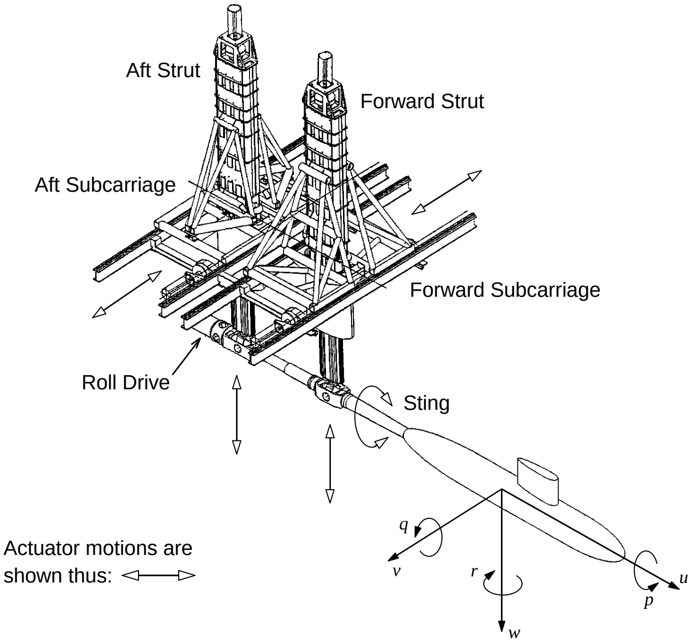

Figure 3.6 - Marine Dynamic Test Facility.

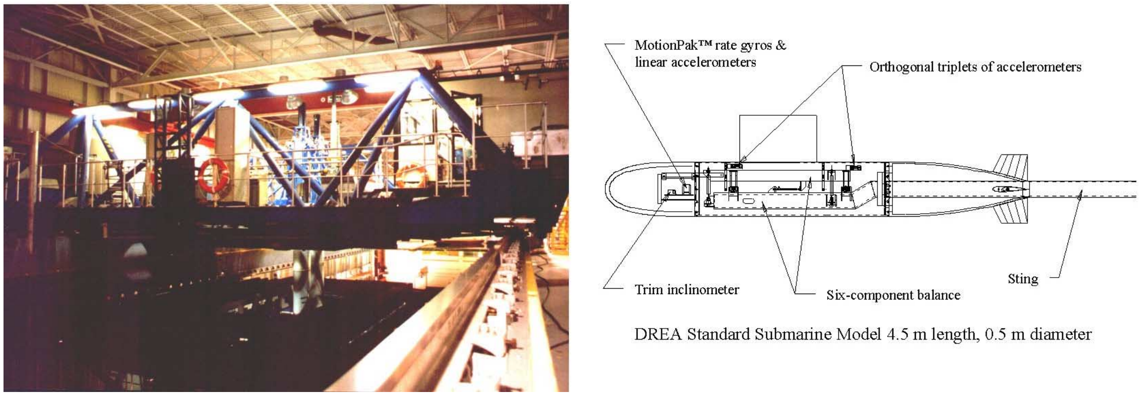

Figure 3.7- Left, MDTF on the towing tank carriage. Right, sting-mounted submarine model with internal balance.

Manoeuvring trials, analogous to aircraft flight testing, are included in the trials program conducted on at least the first-of-class of each new ship and submarine design. Other elements of the overall trials program that may be impacted by, or impact, the ship's dynamics, include powering, seakeeping, and special requirements such as flight deck certification.

Manoeuvring trials confirm that a ship is acceptable with respect to stability and controllability, while decelerating and accelerating, at low and high speeds, and in deep and shallow water. A past difficulty, accurate trajectory tracking, has been considerably alleviated by the availability of GPS. For submarines, manoeuvring in the vertical plane is more critical to safety than manoeuvring in the horizontal plane. Accurate trajectory tracking in the vertical plane generally requires a well-instrumented test range.

A typical manoeuvring trials program for a naval vessel would include:

- Turning tests: from a straight course, the rudder is deflected and held at a fixed angle. The defining parameters of the turn, figure 3.8, must meet acceptance criteria.

- Spiral manoeuvres: from a steady turn, the rudder angle is stepped through a number of values, holding each until a steady turn rate is reached, through to reverse rudder, then back to the original value (e.g., 10 deg. port to 10 deg. starboard, and back to 10 deg. port, in ±2 deg. increments). It is not unusual for a ship to be designed only marginally straight line stable or even slightly unstable; the degree of instability corresponds to the extent of the hysteresis loop in the yaw rate – rudder angle diagram, figure 3.9.
- Zig-zag manoeuvres: from a straight course, the rudder is deflected and held until a specified heading (usually equal in magnitude to the rudder angle) is reached, reversed until the opposite heading is reached, and so on, figure 3.10. The overshoot in heading at each rudder reversal is an indicator of controllability.

For submarines, these trials are done only for horizontal manoeuvres; the first two are not applicable to vertical manoeuvres for obvious reasons. Vertical zig-zags are possible, but are generally restricted to just one sternplane reversal, thereby constituting a simple depth change manoeuvre. A submarine may be straight line unstable in the horizontal plane, but is invariably required to be stable in the vertical plane (where it will also be directionally stable).

The IMO standard for manoeuvrability [IMO (1993)] includes criteria for judging standard turn and zig-zag manoeuvres. Emergency stopping ("crash-back") and a number of other standard tests must also be conducted to completely characterise stability and controllability. For surface ships, manoeuvrability can be significantly affected by sinkage and trim, so it may be required to repeat key tests for different loading conditions.

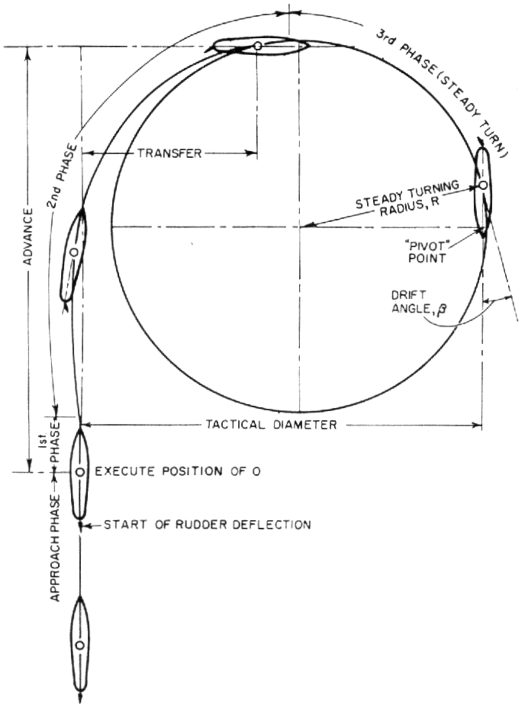

Figure 3.8 - Ship turning test (from [Lewis (1988)]).

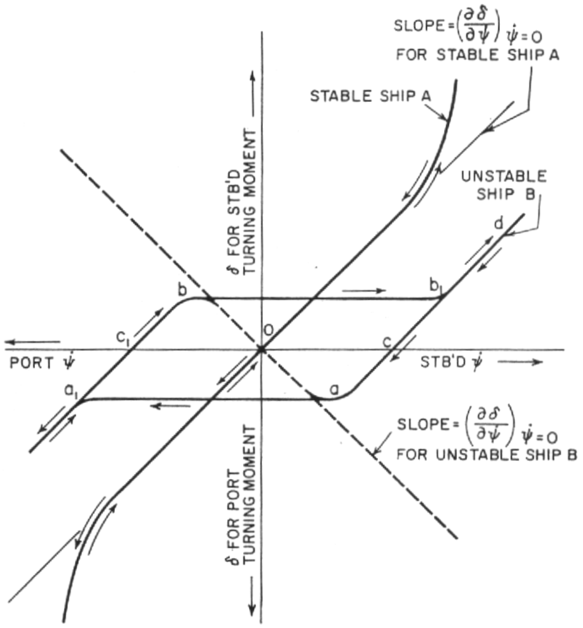

Figure 3.9 - Spiral manoeuvre: yaw rate – rudder angle diagram (from [Lewis(1988)]).

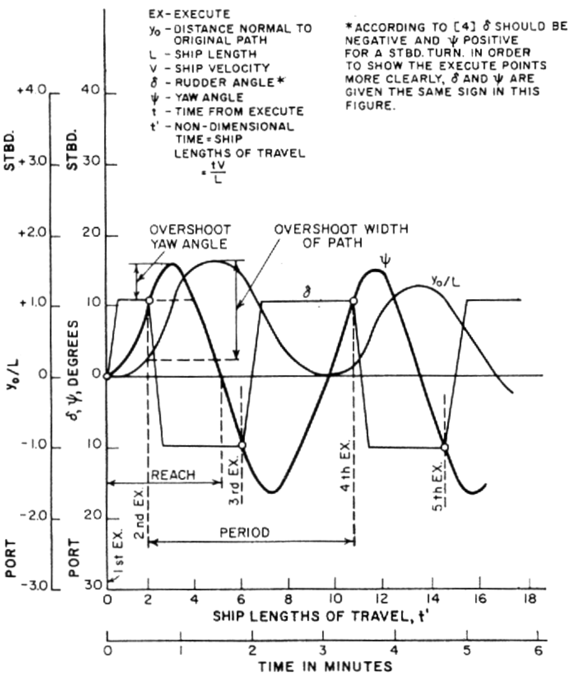

Figure 3.10 - Zig-zag manoeuvre (from [Lewis(1988)]).

3.6 INSTRUMENTATION FOR SYSTEM IDENTIFICATION

3.6.1 General Aspects

Although the choice and location of sensors also could be considered part of the experiment design, this section is mainly focusing on typical instrumentation for vehicle modelling. Simulation fidelity and accuracy of the system identification results depend directly on the quality of the measured vehicle data. Hence the design and installation of the entire system must be carefully evaluated at the outset of a program. Evaluation criteria should include:

- quality of sensors: range, accuracy, repeatability, noise level, susceptibility to temperature drifts, etc.
- effects of filtering, time skew
- sampling rate,
- method of time correlation for different data sources
- ability to calibrate sensors and how various calibration methods will effect the final outcome of the process
- ability to discern the failure of sensors during the test program
- ability to perform data compatibility checks using analytical redundancy

In each of the four domains, highly sophisticated sensing and data acquisition systems are available. To reduce the time required to perform a specific vehicle test program, integrated instrumentation suites have become an area of increased effort for most test organisations. In the sections that follow, examples of typical instrumentation suites for land, air and sea vehicles will be presented.

3.6.2 Land Vehicles

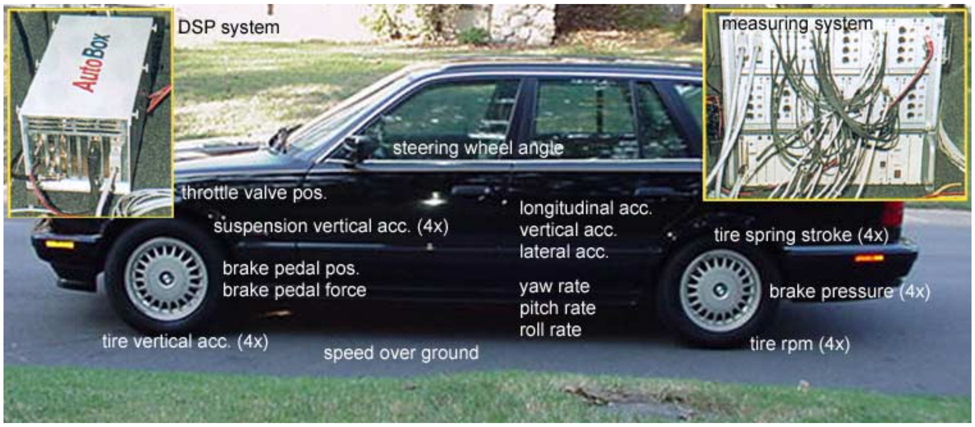

Figure 3.11 - A typical land vehicle instrumentation suite.

Figure 3.11 depicts a typical instrumentation suite for an automobile test program. Similar systems are employed for truck or tank testing, with obvious differences in parameter choices. As with all instrumentation systems, care must be taken in choosing the sampling rates, sensor bandwidths, and filtering systems to ensure that relevant dynamics are captured by the system while keeping the volume of recorded data to a minimum, and while avoiding unwanted artifacts of sampling and digitization. Some dynamic tests, particularly those concerned with suspension systems, drive sampling rates to their highest limit while the motion between suspension and rotating components creates complexities in how sensor data is transferred between the fixed and moving reference frames.

Typical instrumentation suites are designed to capture a force, position or acceleration of interest with minimum sensitivity to other orthogonal signals. Vertical suspension motion is usually measured by an accelerometer and/or a displacement transducer such as an LVDT or string potentiometer. Lateral and longitudinal forces are measured by instrumenting the ball joints of the subject vehicle and using them to measure load in those directions. Recent advances in automotive instrumentation have resulted in transducers which are situated between the wheel and hub. Such devices are designed to measure the three linear loads and three moments which are imposed on the vehicle hub. Such devices are designed to be broadly applicable to a broad class of vehicles.

Data acquisition systems used for automotive instrumentation are typically composed of two primary components, a signal conditioning box and a lap top computer. The signal conditioning box is responsible for instrument excitation, signal filtering and amplification, calibration, and sometimes sampling. The signal conditioning box is typically powered by the 14V DC vehicle power supply. The laptop computer is used for permanent data storage and in-test data review and verification. It has data processing and plotting software for instrumentation checkout and review. The ability to rapidly verify the integrity of the recorded data frequently is one of the most important features of a vehicular data acquisition system.

3.6.3 Air Vehicles

The sensors that are mounted in an airplane for normal flying are usually not sufficient, in terms of the number of signals and accuracy, for system identification purposes so additional sensors have to be mounted. Due to safety reasons and/or the burden of paperwork required to analyse and validate the structural implications of the installation, the process used for most instrumentation systems in aircraft avoids drilling holes in the aircraft structure. Thus, the installation of additional sensors and test equipment for modelling and system identification purposes is usually performed using temporary fixtures.

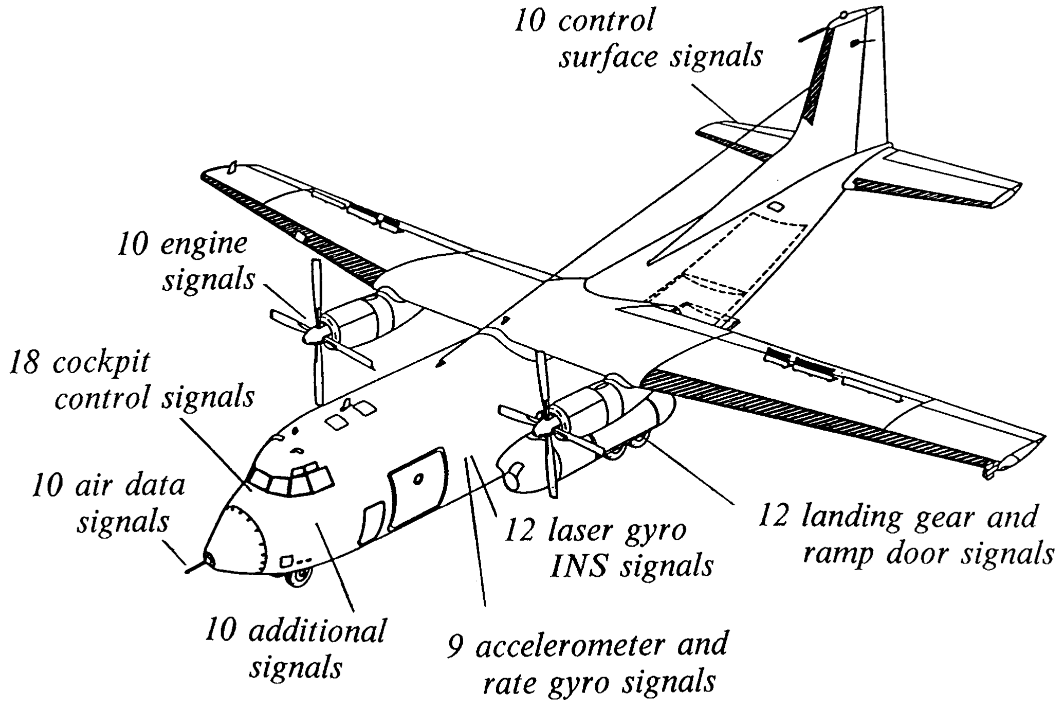

Figure 3.12 - Sensors for the C-160 data gathering program

As an example of the complexity of aircraft instrumenation systems, for a modelling flight test of the C-160 Transall [Jategaonkar *et al.* (1994)], a total of 91 physical parameters where recorded using basic aircraft sensors and additionally installed sensors. Measurements included angular rates, linear and angular accelerations, air data signals, angle-of-attack and sideslip and all control surface deflections (see Fig. 3.12).

If aeroelastic modes have to be taken into account for high performance or large aircraft additional accelerometers, gyros, or strain gauge measurements must be added to the typical instrumentation suite. Due to the recently increased accuracy of the satellite data, Differential GPS is now routinely used to replace radar tracking as a means for obtaining position data, although this often requires a coordinated ground station with ground to air telemetry of GPS error estimates.

Rotorcraft instrumentation systems are similar to those employed in fixed-wing testing but have several additional obstacles to overcome:

- Due to the high vibration level for rotorcraft, additional filtering techniques have to be used for data pre-processing.
- Measurement of air data parameters is very difficult in low-speed and hover due to the influence of the downwash from the main rotor on the corresponding sensors.
- Often, measurements of the rotor states are desired, requiring a robust and efficient technique to transfer the data measured in the rotor reference frame, which is rotating, into the more stable fuselage reference frame where recording or transmitting devices are usually installed

3.6.4 Submarines and Sea Vehicles

The standard manoeuvring trials outlined previously in this chapter require only some means of trajectory tracking in addition to the ships own instrumentation (rpm, speed, heading, etc.). Tracking may be accomplished on an instrumented test range, by ship’s own, or a dedicated, INS package, or by GPS. More elaborate instrumentation for a seakeeping and loads experiment is illustrated on figure 3.13. In addition to standard motion measurements, data gathered include transient impact (slamming) pressures on the hull, hull girder strains, and seastate parameters measured from the ship and from wave buoys.

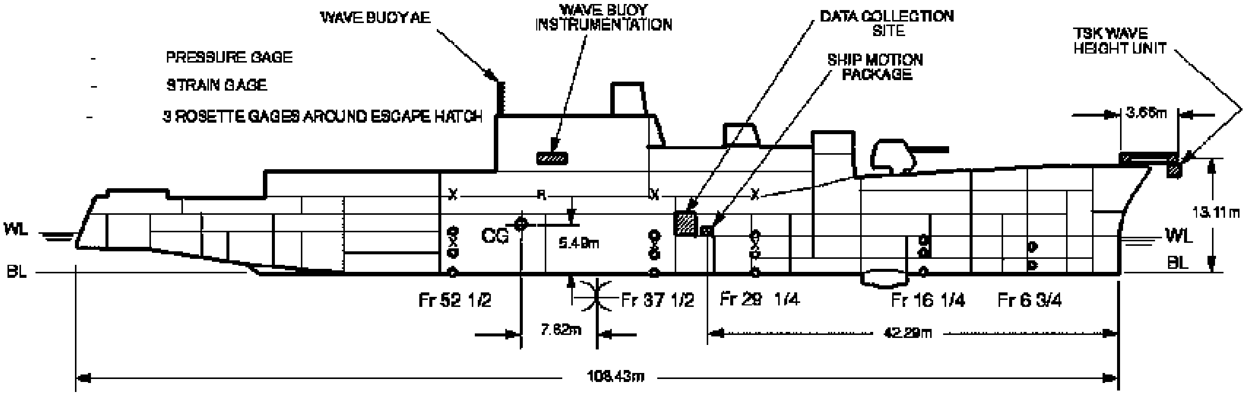

Figure 3.13 - Instrumentation for a seakeeping and loads trial.

A significant trials requirement for sea vehicles is propulsion testing. Propeller thrust and torque are measured for various manoeuvres, seastates, and loading conditions. In the case of severe propeller cavitation problems on surface ships, observation of the cavitation may be required. This is costly and intrusive if viewing and illumination ports have to be installed in the ship's hull [Kennedy *et al.* (1989)]. Table 3.1 lists some minimum requirements for sea trials instrumentation; they are generally easily exceeded by modern equipment.

Table 3.1 - Minimum requirements for trials data measurement and accuracy.
(Adapted from Lloyd's Register (1999))

	Parameter and Measurement Rate:						
Manoeuvre:	**Time**	**Position**	**Forward Speed**	**Heading**	**Rudder Angle**	**Engine RPM**	**Rate of Turn**
Turning Circles	Cont.	Every 45° in heading.	Lesser of every 10 s. or every 30° heading.	Every 5 s.	Every 45° in heading.	Every 45° in heading.	Every 5 s.
Pull-outs	Cont.	—	—	Every 2 s.	Every 2 s.	—	Every 2 s.
Stopping	Cont.	Every 20 s	Every 5 s.	Every 20 s	Periodically	Every 5 s.	—
Zig-zags	Cont.	At least 5 times.	Every 5 s.	Every 2 s.	Every 2 s.	Every course crossing.	Every 5 s
Spirals	Cont.	—	Each steady turn rate.	Every 2 s.	Every 2 s.	Each steady turn rate.	Every 5 s
Man Overboard	Cont.	Lesser of every 20 s. or every 45° heading.	Every 5 s.	Every 2 s.	Every 2 s.	When rudder reversed.	—
(Minimum Required Accuracy)	± 1 s.	± 10 m.	± 0.5 kt.	± 0.5°.	± 1°.	± 1% of initial.	± 0.05 °/s.
Cont. = continuous. (All parameters are also to be measured at the initial and terminal points of each manoeuvre.)							

Tracking submarine manoeuvres can be done with an INS package or on an (acoustically) instrumented test range if sufficient depth of water is available.

3.7 MATHEMATICAL MODELS AND NUMERICAL PROBLEMS

Numerous powerful identification methods and software tools are currently available to aid the researcher and engineer in the system identification process . Despite the capability of these tools, further development is required to improve the efficiency and robustness of the process. Streamlining the processes through the development of integrated tools is a logical next step.

In addition, several sophisticated system identification methods developed outside the vehicle domain could provide further performance improvements or advantages for the vehicle analyst. A typical example is the technique known as "multiple shooting" which has been successfully used to analyse chemical reaction kinetics. The focus of current effort on unstable aircraft system identification has led to increased emphasis on techniques such as regression, filter error methods and equation decoupling.

Finally, further effort is being placed on "Fast Identification Techniques" which reduce the time required to generate useful results after data are collected. The use of recursive algorithms to provide model updates, speeds up the process by allowing the employment of high performance parallel-computers and workstation-clusters.

Further areas of future development include:
- On-line parameter estimation
- Advanced time or frequency domain identification
- Algorithms: equation error, output error, filter error, multiple shooting, recursive
- Optimisation: search algorithms (evolutions strategy, simplex method), gradient-based algorithms (Gauss-Newton method)
- Statistical analysis of parameter estimates
- Improved procedures to minimise the time needed for modelling/validation
- Improved application of numerical tools like neural networks, fuzzy systems, wavelets and data mining
- On-line system identification for health and usage monitoring (failure prediction)
- Sensitivity and uncertainty studies
- Automated model structure determination

Another area of interest is the development of modelling and simulation tools for faster economic and effective vehicle development, planning of tactical missions, and determination of the best vehicle concept from a number of proposals.

3.8 CURRENT ACTIVITIES AND TECHNICAL CHALLENGES

3.8.1 Multidisciplinary Modelling and Simulation

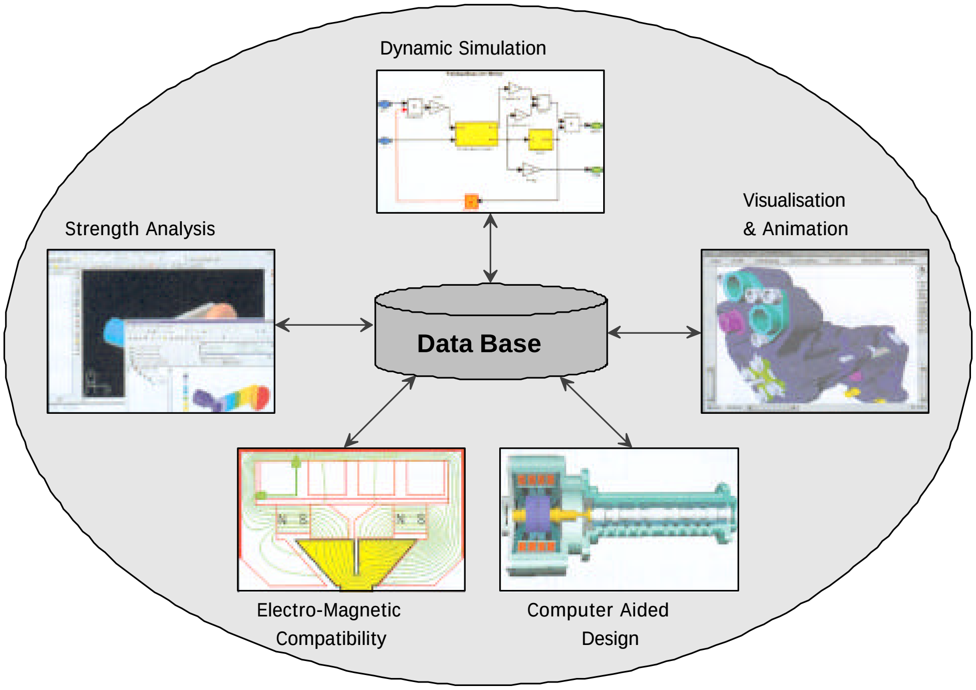

Figure 3.14 - The Potential Architecture of Multi-Disciplinary Modelling

The integration and evaluation of advanced multidisciplinary modelling concepts leads to the coupling of computational fluid dynamics (CFD) calculations with flight mechanics and structural mechanics analyses. As an example, MEGAFLOW, a joint project between DLR, EADS and German Universities, aims at developing a highly complex and advanced software system for the aerodynamic simulation of complete aircraft in cruise as well as in take-off and landing configurations, meeting the requirements of industrial implementation.

The design of new commercial and transport aircraft relies, besides on the conventional approaches of wind-tunnel and flight tests, more and more on advanced numerical flow simulation techniques. The most complex scenario will call for the calculation of three-dimensional, viscous, turbulent flows around complete aircraft.

The combination and interaction of mechanical, hydraulic, electrical and electronic functions and components leads to mechatronic systems (see Fig. 3.15).

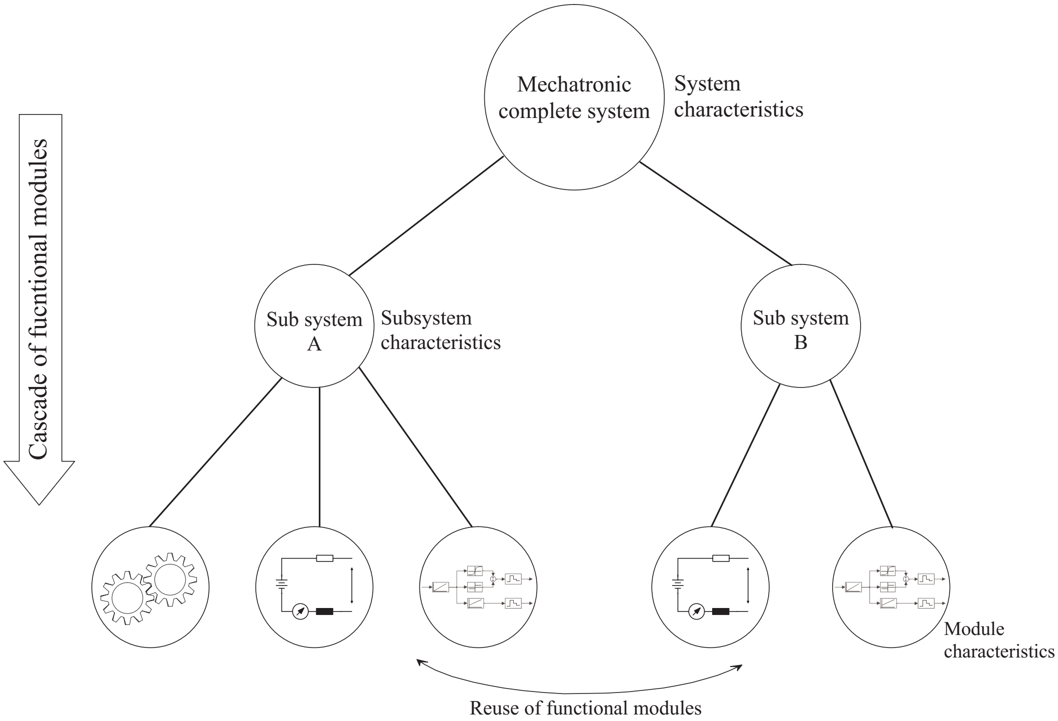

Figure 3.15 - Structure of a mechatronic system

A lot of development effort has gone into mathematical models that describe in detail the behaviour of mechanical-electrical systems like servos and actuators. This is useful in optimising existing, and developing new, mechatronic systems. An approach based on cascading of simpler subsystem models is adopted to derive the model describing the complete system. The subsystems are formed based on functionality and, once derived, functional modules are reused in several subsystems. In principle, this is the basic approach to arrive at the model description of the complete system, be it mechatronic or a global aerodynamic model.

3.8.2 Integration of Generic Modelling and Identification

For high fidelity modelling of helicopters, an integrated modelling and identification approach is being developed to improve model accuracy and fidelity. A clear example of this development is the simulation software package, HOST (Helicopter Overall Simulation Tool), which was augmented with an identification option. This modification allows the utilisation of the complete nonlinear simulation while identifying certain effects using parametric submodels. Thus the same tool can be used for improving the simulation model using system identification and for subsequent predictive simulation with the enhanced model.

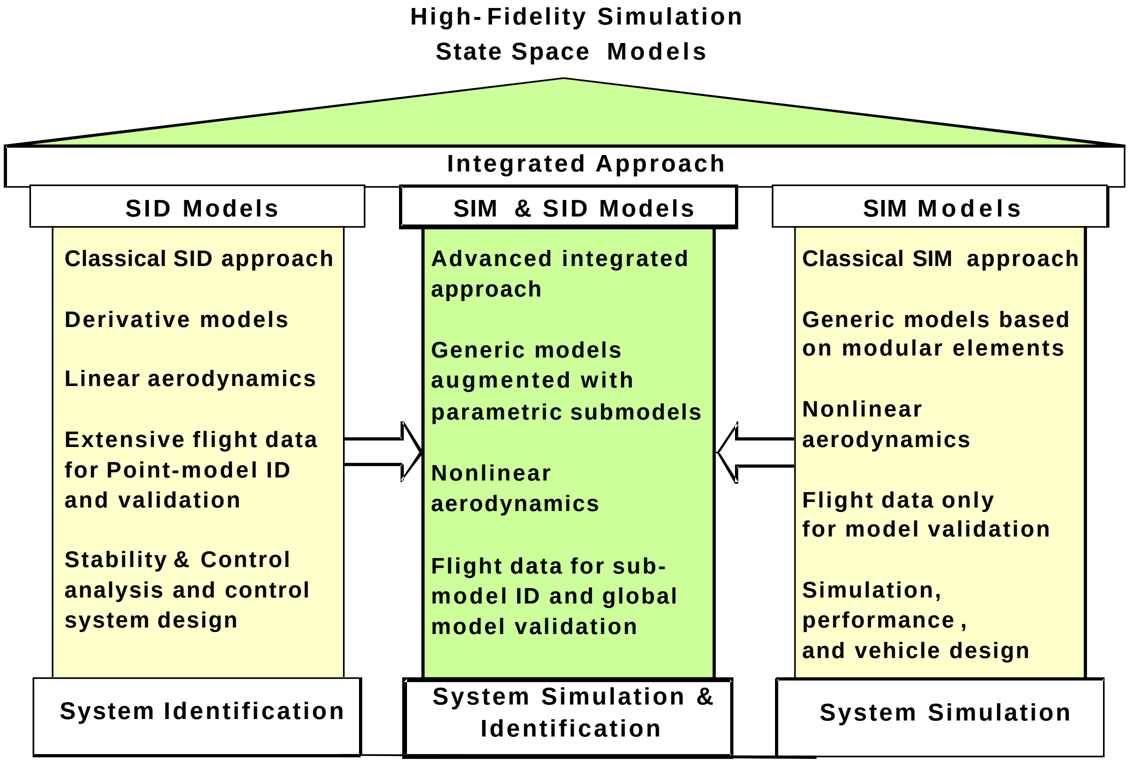

Figure 3.16 - Integration of system identification and simulation

3.8.3 Control-Oriented Modelling and System Identification

Control-Oriented System Identification deals with the problem of resolving real system behaviour with simple models and defined uncertainty descriptions. The idea is to discern the relevant features of a system with respect to a specific performance objective, and represent them in the simplest possible way (i.e. in model development). Remaining behaviours of the system, as revealed in experimental data, are then captured by an appropriate uncertainty description. In following this approach, the models become far more descriptive and understandable, particularly for specific system control problems.

The value of Control-Oriented Modelling and System Identification is readily apparent in the consideration of feedback control problems. To leverage the most from feedback control it is usually not enough to simply regard the mismatch between model and real system behaviour as "noise". Rather, this mismatch is more appropriately factored into two parts. First, some mismatch between modelled and real behaviour is the result of intentional under-modelling of the system (that is, choosing a low complexity model that captures the most relevant features while ignoring the rest). The remaining mismatch is then "noise" in the sense that it is caused by forces external to the object that we have abstractly attempted to isolate as a "system". With this information in hand, the feedback control system designer can better consider the tradeoffs and limitations of model complexity and final closed-loop system performance.

For any specific system and environment, inherent uncertainties originating from model simplifications, simplified vehicle dynamic conditions, and other potential unknowns have to be taken into account. For complex systems, mathematical models may depend on a large number of parameters. The values of these parameters can only be determined with a certain level of accuracy. Also, complex non-linear characteristics are often not modelled, either because they are unknown or because they would complicate the model too much (and neglecting such characteristics can be justified). Due to these uncertainties, discrepancies exist between the dynamical behaviour predicted by the model and that of the real system.

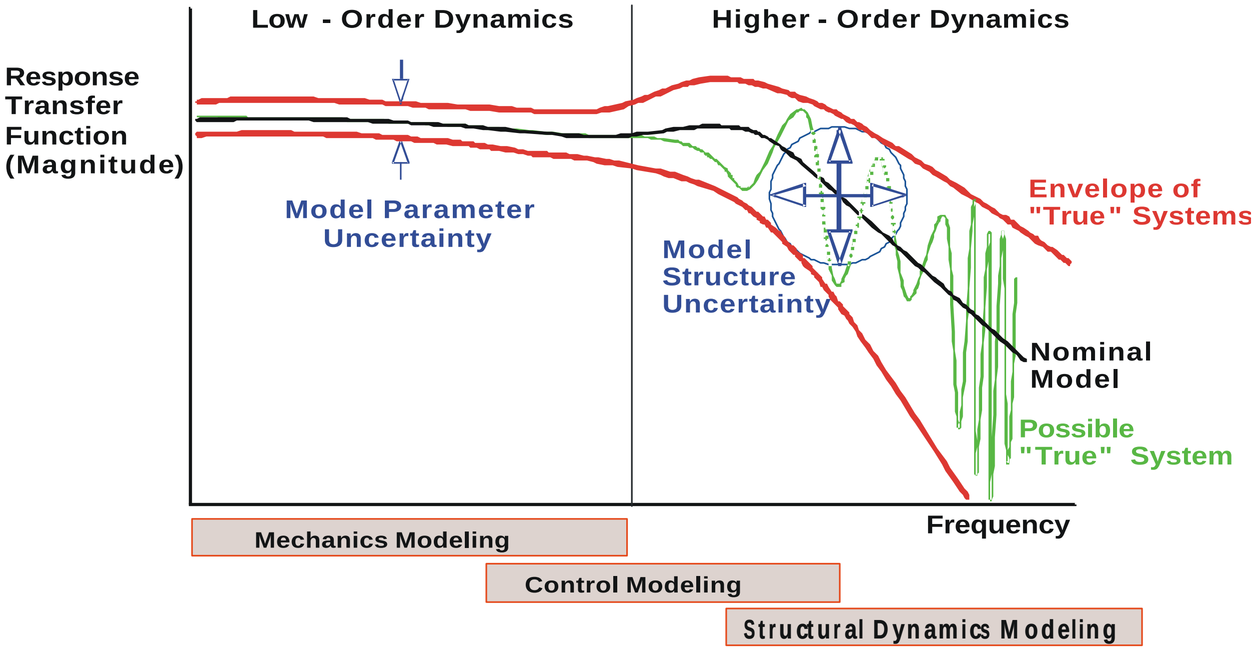

Fig 3.17 - Different types of uncertainty

In order to control complex dynamic systems, a control system is required which works satisfactorily under all circumstances that the system will meet in practice. Since control laws are generally developed using a simplified model, they have to be robust against the discrepancies, between the model and reality. Including the uncertainties in the identified parameters in the derived model, leading to a “fuzzy” model, would allow direct evaluation of the control system while accounting for the model uncertainties.

3.8.4 Redundancy Concepts and Fault-Tolerant Systems

A fault-tolerant system is one that can sustain a reasonable number of process or communication failures, both intermittent and permanent. Increased standards for high reliability demand multiple redundant subsystems and control actuators. Thus, the failure of any individual component can be mitigated by auxiliary, redundant components. While the conventional approach to ensure the fault-tolerant performance of an entire system is based upon hardware redundancy for critical parts and subsystems, modern concepts use advanced techniques to attain the desired degree of safety. They employ the reconfiguration of the whole control system to make the most effective use of remaining capabilities.

These methods, known as analytical redundancy concepts, require the capability of detecting, identifying and evaluating critical failures and their time-dependent behaviour in order to initiate further procedures. The basis for identifying the occurrence of a system failure usually is a nominal model of the system which defines its normal behaviour. Different methods like state estimation, parameter identification, or neural network approaches are applied to analyse apparent divergences from normal operation. With regard to the preservation of overall system functionality and robustness, the specific characteristics of the detected faults should lead to an appropriate reconfiguration of the remaining unfailed system components under real-time conditions. In the case of incipient faults, the resulting effects might be considered, identified and even eliminated by online-calibration.

It can be observed that there is a clear trend for the integration of fault-tolerant robust control and real-time fault detection concepts. In the effort at increasing reliability and reducing costs this link from modelling to robust control will become more and more important in the whole field of safety-relevant technologies.

3.9 FUTURE ACTIVITIES AND CHALLENGES

3.9.1 General

The system identification and modelling community is working in the following areas

- Optimal input design,
- Model structure determination techniques
- Efficient algorithms to process large amount of test data
- Robust and efficient parameter estimation considering uncertainties, particularly process noise (atmospheric disturbance, sea roughness)
- On-line and recursive system identification
- Special applications with increasing complexity and nonlinearity
- Computational aspects (e.g. use of heterogeneous workstation-clusters)

3.9.2 Land Vehicles

- Monitoring, failure prediction and prediction of dangerous situations for automatic prevention of accidents and damages, diagnostics of unexpected behaviour or accidents
- Modelling of intelligent vehicle and transportation systems for autonomous vehicle control and vehicle operation
- Pre-computed tactical missions of vehicles integrated in the military unit and central guidance of operations
- Identification of complete vehicle models from input/output measurements without dividing the vehicle into components
- Including moving load in simulations
- Improve experimental facilities with hardware-in-the-loop simulation and with inclusion of man as operator
- Improve the modelling of vehicle ground interfaces such as, combining interactions between tire or track models with representative soil/terrain models, to get realistic force inputs for the vehicle simulations.

3.9.3 Air Vehicles

- Modeling of aeroelastic effects like structural coupling and their influence on automatic flight control systems
- Development of high fidelity and high bandwidth models
- Advanced modeling of unsteady aerodynamic effects
- Flight in turbulence
- Flight at extreme flight conditions
- Landing with high sink rate (e.g. STOL, helicopter, tilt rotor, etc.)
- Development of global aerodynamic models valid over the complete flight envelope
- Modelling new control device effects (e.g. jet blowing, active control etc.)
- Sensitivity and uncertainty studies
- Automated model structure determination
- Improved procedures to minimise the time needed for modelling/validation
- Improved application of numerical tools like neural networks, fuzzy systems, wavelets and data mining
- Hybridisation of different modelling concepts, integrated SIM+SID approach to reduce discrepancies in rotorcraft model fidelity
- On-line system identification for health and usage monitoring (failure prediction)

- Blade element rotor modelling
- Accurate measurement of speed, models for helicopter air data system

3.9.4 Sea Vehicles

- Methods of improved automatic steering control
- Subsurface hovering and depth control
- Active sea-keeping enhancement
- Control in shallow and confined water
- Development of criteria to assess closed loop stability and controllability
- Optimisation of manoeuvres
- Improved non-linear models for design and prediction
- Platooning of UUVs
- Ship/helicopter and ship/aircraft interoperability

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Chapter 4 – Control of Vehicles and Vehicle Systems

4.1 INTRODUCTION - The Objective of Vehicle Control

The objective of vehicle control is to enable the operation of the vehicle so that the intended mission can be achieved economically and safely under all conditions for which the vehicle is designed. Besides control of the velocity, direction, and position of a vehicle, adequate control of its subsystems and components, such as flaps and undercarriage in case of an aircraft, is also required to achieve the intended mission.

In this chapter an overview is given of vehicle and weapon system control in the context of vehicle manoeuvring and vehicle component control for vehicles in the land, air, sea, and space domains. The overall objective is to identify similarities and differences between the domains, as well as describing the state of the art of technical challenges and solutions for each domain. A short description of the control systems, their primary objective, and the level of automation for each specific domain are presented in the following subsections.

4.2 CONTROL OF LAND VEHICLES

4.2.1 General

The following section addresses military land vehicles. In US terminology, land vehicles are divided into three classes:

- **Combat vehicles** – These are armored and armed vehicles whose mission is to engage an enemy using direct or indirect fire. Variants within families of vehicles may also be included in this class, even though they do not have a direct combat role (e.g., a bridge carrier on a tank chassis). Formerly, owing to the weight and ground pressure of armored vehicles, as well as the general robustness required by their mission, this class of vehicles was exclusively full-tracked. However, emerging changes in US strategic deployability doctrine have required wheeled vehicles to be re-examined in this role. Vehicles in this category almost universally provide a fording capability, and the lighter variants may swim. Numerous schemes have emerged over the years to provide swimming kits for the heaviest vehicles (usually tanks) but none have proved feasible.

- **Tactical vehicles** – These are specialized military vehicles with adaptation for cross-country travel, obstacle negotiation, fording or swimming, and self-recovery. Wheeled vehicles in this class are often equipped with central tire inflation management systems to allow ground pressure to be changed on the move. Most examples of this class are cargo carriers, and most are wheeled. Ackermann steering layouts prevail, although articulated vehicles and skid-steered rubber-tired vehicles have had some limited application. These vehicles are unarmored, but may be furnished with applique armor kits for mine resistance and protection from small arms fire. Armament may be absent or limited to defensive machineguns.

- **Administrative use vehicles** – These are off-the-shelf or slightly modified commercial vehicles used for non-combat missions. They may have limited off-road utility, but are primarily intended for use on roads. They are almost universally unarmed and unarmored. Except for a few vehicles with specialized equipment for snow or swamps, these are civilian vehicles in military livery.

4.2.2 Definition of Frames of Reference

Roll refers to rotation about a horizontal axis parallel to the longitudinal axis of the vehicle. Pitch is rotation about a horizontal axis perpendicular to the longitudinal axis of the vehicle. Yaw is rotation about a vertical axis perpendicular to the ground plane. Except for rare exceptions, land vehicles do not have controllable roll and pitch. Yaw is synonymous with steering control.

For references to turret controls, the roll and pitch axes are assumed to rotate with the turret (i.e., the roll axis remains parallel to the direction of the primary weapon, and the pitch axis remains perpendicular to it.). In land vehicle weapons, the term traverse refers to motion about the yaw axis, elevation refers to motion about the pitch axis, and cant is motion about the roll axis. With rare exceptions, control is only provided for traverse and elevation, with no control for cant (ballistic correction for cant is provided by adjusting traverse and elevation).

4.2.3 Objectives of Vehicle Control

The objectives of land vehicle control are

- Driving direction
- Directional stability
- Vehicle speed
- Distance control
- Traction forces
- Braking forces
- Optimization of fuel efficiency

In tactical situations the vehicle control designer must also consider:

- Convoy operations
- Location of the vehicle in a hidden position
- Location of the vehicle in a firing position
- Firing during high vehicle speed

To meet these objectives, navigation controls and some level of an information /guidance system (e.g. IFIS) are required.

4.2.4 Manual Control

The following control elements are manipulated by the driver during normal operation:

- A steering mechanism, either a steering-wheel, such as in most trucks and some tanks, or a variety of other mechanisms known as laterals, yokes, t-bar or a joystick in other tanks. Appendix III provides an enlightening discussion of the evolution, function and advantages and disadvantages of the different alternatives for steering elements in tanks.
- An acceleration-pedal
- A braking-pedal
- A clutch-pedal
- A gear-stick for manual gear shifting or, in case of automatic gears, switches for program selection of the gears

Furthermore the driver activates special features manually, such as

- Differential locking, providing increased traction when necessary
- All wheel drive activation, again for traction purposes
- Tire inflation pressure controls to vary the level of inflation, based on the terrain conditions

While the majority of these systems are normally mechanized using pure mechanical or hydraulic elements, recent efforts in control-by-wire are being pursued to simplify the control task for the driver. A more complete discussion of control-by-wire for all domains of vehicles is found later in this chapter.

4.2.5 Automatic control of components for the driver's aid

In carrying out the control functions the operator can be supported by automatic control systems. Those systems include sensors, computers and actuators which enable higher driving safety as well as better mobility:

- traction-control (ASR)
- braking force control (ABS)
- stability control (ESP)

The above-mentioned control systems are in general use in cars; however they have not yet found general application in military vehicles. Systems such as tire inflation, differential locking, and torque distribution, which are currently manual systems, are prime candidates for automation, and devices such as a cornering speed predictor and a rollover warning system would increase safety in difficult terrain. A more complete overview on the state of the art of intelligent control systems for land vehicles is given in Appendix II.

4.2.6 Crew Member Considerations

New devices for automatic control, information and navigation systems are required to reduce the number of crew members in a tank, especially in the main battle tank. This is desirable especially for the development of small and low silhouette armoured vehicles. In general, the main battle tank has four crewmembers:

- Commander
- Driver
- Gunner
- Loader

An automatic loader allows the reduction of the crew from four to three. This, so far, has been implemented in Russian and Swedish tanks. Various studies have been carried out to achieve a further reduction to two crew members, the tank commander and the tank driver. In this scenario, it is envisioned that either crew member can take on the role of the gunner, when needed. Furthermore it is expected that the both crew members will be able to carry out their functions interchangeably. In this case, the driver and the commander would have control stations with essentially the same capabilities.

Appendix III provides further information regarding crew stations and roles in typical main battle tanks.

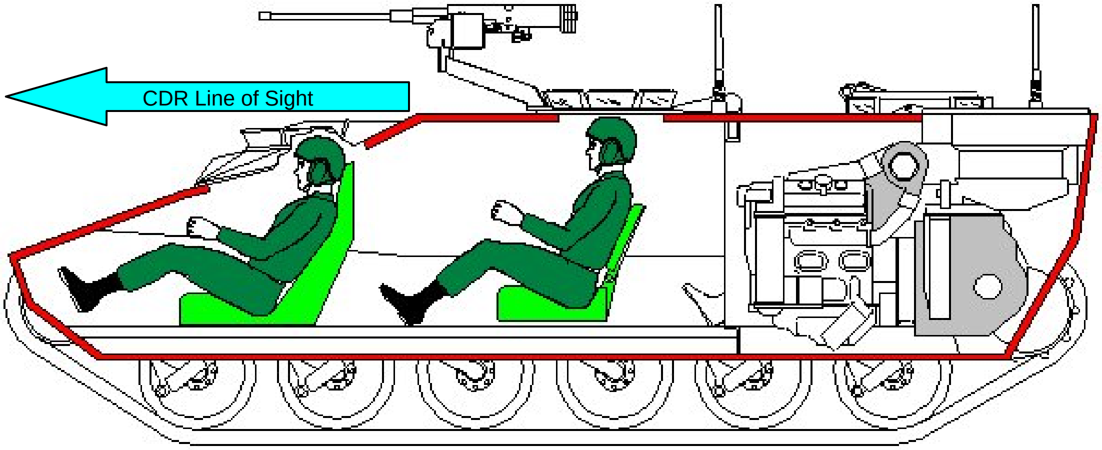

Fig 4.1 - Supine Tank Driver Seating

Combat vehicle drivers are typically seated in the conventional vertical posture. Some modern vehicles put the driver in a supine position, but this measure is primarily intended to minimize height of the vehicle, rather than for ergonomic reasons (Fig. 4.1). The vehicle crew is subject to impacts and to high-amplitude vibration, but does not experience high sustained accelerations (g-loads) in any axis. Experiments were carried out in the US in the mid-1970’s on prone driver positions with motorcycle-like controls (Figure 4.2), but this arrangement had undesirable ergonomic consequences, and prone crew positions have not been further pursued.

Because the driver is primarily concerned with controlling movement of the hull, his station is almost universally located in the hull, with the driver facing front. Two notable exceptions are worthy of mention.

Fig 4.2 - US Experimental Vehicle Used to Investigate Crew Seating Positions

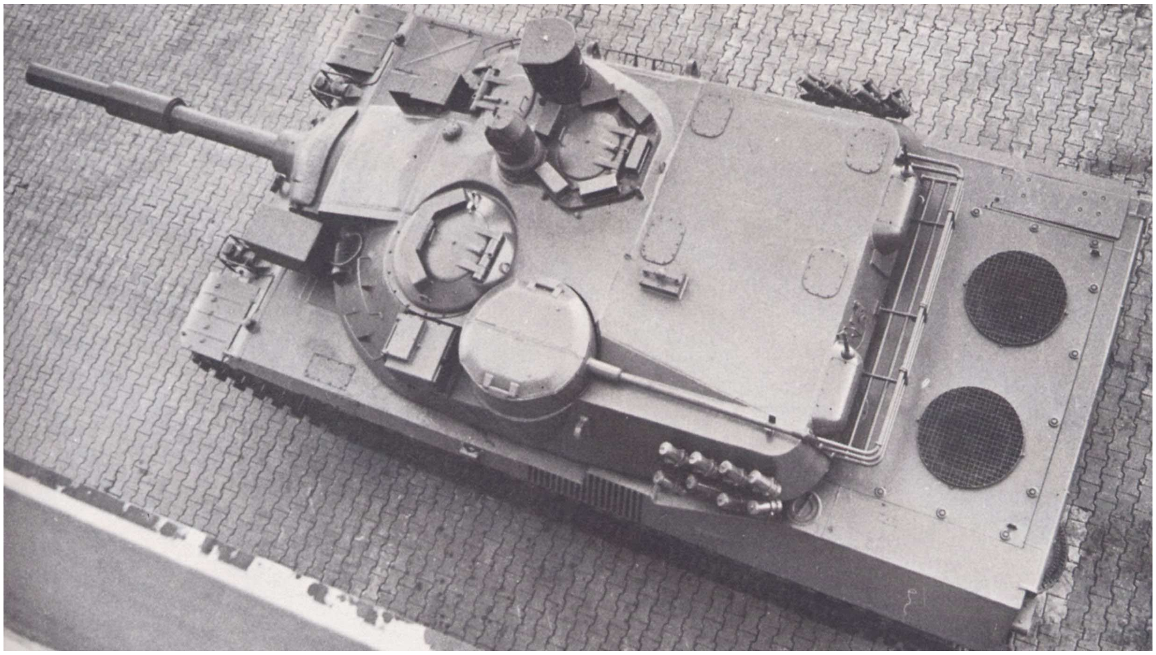

Fig 4.3 - An overhead view of MBT-70

The MBT-70, a joint tank development project between the US and the FRG, featured a driver's station in a rotatable capsule in the turret (Fig. 4.3). The capsule was arranged to counter-rotate against turret motion so the driver always remained facing the front of the hull. The advantage of this system was that length and height of the hull could be reduced because no space was required outside the turret ring for a hull-mounted driver's station. When the vehicle was in reverse, the capsule rotated so that the driver faced the direction of travel. In practice, however, the arrangement was complicated, and offered few real advantages.

The Swedish Stridsvagn-103 (S-tank), Figure 4.4, featured a three-man crew. The commander's duties were relatively conventional, but those of the other two crew members were decidedly not. The driver/gunner was seated facing forward with an integrated T-bar control, which served as driving control while the vehicle was moving, and as gun-laying controls when it was stationary. The turretless vehicle had a fixed 105 mm cannon that was trained using counter-rotation of the tracks, and laid using hydraulic control of the 1st and 4th roadwheels on the suspension. The entire hull was effectively aimed, like a fighter plane, to point the gun. The radio operator, whose station faced the rear of the vehicle, was provided with a redundant set of driving controls. Because the vehicle lacked a turret, the only way to keep the gun and glacis armor pointed in the direction of the enemy when retrogressing was to have the vehicle back up. Although the S-tank was admirably suited for Swedish ambush tactics in restricted, forested terrain, its lack of a shoot-on-the-move capability made it unsuitable for general use. The US evaluated the S-tank in the mid-1970's, but concluded that the workload of the driver/gunner was excessive.

Fig 4.4 The Stridsvagn-103

4.2.7 Navigation Controls

While engaged in combat, land vehicles must react to a rapidly changing battlefield. They often utilize features of the terrain too small to show on maps (micro-terrain) in order to gain protection from enemy observation and fire, and to gain advantageous firing positions and routes of advance. Therefore, autopilots and similar automated driving aids are not yet used in combat. Tactical and administrative use vehicles, whose movements (particularly in convoy operations) can be planned in greater detail, may be able to use such systems to reduce driver fatigue, or to allow robotic “shepherding”. However, these innovations are still in the early stages of development, and currently rely on well-defined roads which can be easily discerned by robotic vision schemes.

Except for convoy operations, no military land vehicle uses station keeping in the sense that ships or aircraft maintain formation. When units are tactically deployed, combat formations are primarily used to ensure that the unit has 360 degree observation, to maintain dispersion so the unit cannot be simultaneously engaged from any one direction, and to assign fields of fire. However, unlike air and sea vehicles, which all negotiate essentially the same environment simultaneously, the terrain to be negotiated by each vehicle contains unique local features.

GPS systems are fitted in virtually all combat vehicles, and in many tactical vehicles as well. Because of the critical importance of micro-terrain discussed above, these systems are used as adjuncts to maintain correlated maps, rather than as waypoint-route navigators. Exceptions have occurred, such as the well-known envelopment by VII Corps during Desert Storm, when there were few significant map features. However, use of GPS as a navigator in the way that air or sea units use them is impractical. In modern communications environments, GPS-derived position data can transmit the position, speed and direction of all friendly vehicles, but this is primarily a situation awareness function, rather than navigation.

Fig 4.5 - Driver’s station in a French LeClerc tank

Combat vehicles have been equipped with gyro compasses (magnetic compasses being generally impossible to compensate for large rotating steel turrets), for special purposes such as maintaining heading during fording operations, or maintaining orientation through smoke. However, because of the necessity to respond to enemy actions and the micro-terrain, compasses are not generally used for navigation purposes in land vehicles.

The general method of driver navigation is receipt of verbal instructions from the vehicle commander. Such instructions are usually brief, and are supplemented with the driver’s understanding of the tactical context of the situation. The decisions required to meet the intent of such orders are not readily assisted by an automated aid, and are usually solved better by the driver, particularly after he bcomes familiar with the commander’s style of conducting combat operations. A typical driver station, in the French LeClerc Tank, is shown in Figure 4.5.

4.2.8 Main Battle Tank Stabilization Control System.

The principal weapon of a main battle tank is typically a 105 mm or 120 mm cannon mounted in a traversable turret. Since the control of this weapon system is of primary importance to the overall mission success of an MBT, a review of a typcial gun/turret drive (GTD) system is presented here.

Gun elevation and depression is accomplished with a hydraulic cylinder, and turret traverse is accomplished with a hydraulic motor and gearbox, both electronically controlled. The gunner’s sight typically contains an elevation head mirror, which contains a two-axis gyro; drive motor, resolver, tachometer, solenoid brake, and head mirror. In the stabilized mode of operation, gun elevation is slaved with the head mirror in the gunner’s sight, and the turret is similarly slaved in azimuth. This provides the target acquisition and retention capabilities necessary for aiming and firing the weapon when the tank is either moving or stationary.

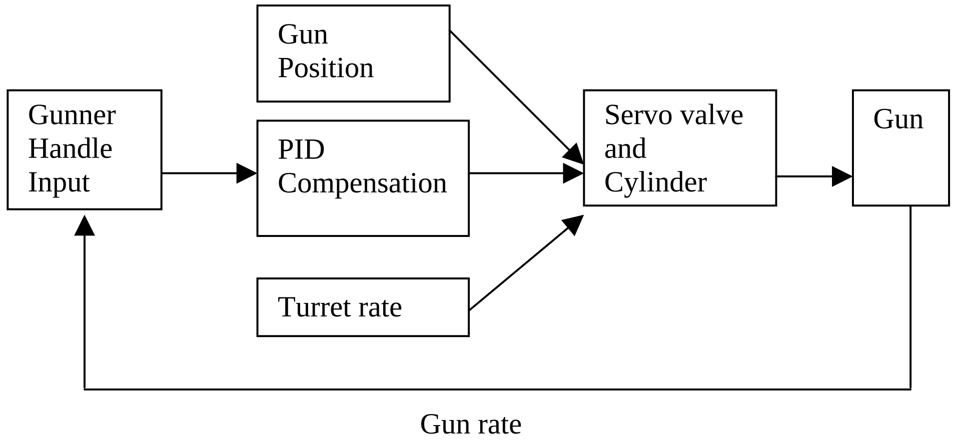

Figure 4.6 - Elevation System Functional Block Diagram

Figure 4.6 provides a block diagram of the elevation system. The control system is of the proportional type, incorporating integral and differential control compensation (PID). Velocity lag error is minimized by using an open loop pitch rate input generated by the turret gyro. During moving vehicle operations, turret pitch rate, measured by the turret gyro, is used as an error feed forward to reduce stress on the closed loop gun stabilization system. Differential pressure feedback (torque feedback) is used to provide additional system damping.

Figure 4.7 is a functional block diagram of the turret control system for the azimuth axis. The azimuth gearbox assembly provides control of the turret throughout 360 degrees of travel. As in the elevation axis, handle and stabilization sensor commands are processed through a PID controller. Open loop yaw rate is sensed to counter rotate the turret thus maintaining a spatial position reference. Errors in this counter rotation are sensed by the azimuth portion of the dual axis gyro mounted on the gunners head mirror drive; differential feedback is used to increase damping.

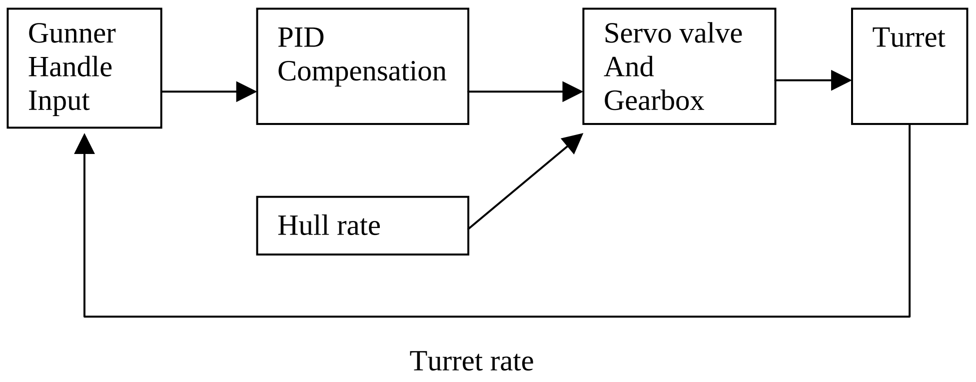

Figure 4.7 - Azimuth System Functional Block Diagram

4.2.9 The future

Development initiatives now being undertaken in the US and elsewhere present new challenges in the area of controls. Advanced systems will feature unmanned platforms, and manned vehicles will have fewer crewmembers. Work remains to be done in the following areas:

- Telepresence – Human operators will remotely monitor and operate unmanned vehicles. New technologies are needed to give the operator a replacement for primary and secondary sensations he would receive if he were actually in the vehicle:
    - Vibration – How can we replace "seat-of-the-pants" cues to terrain roughness so that remote operators will be able to maintain appropriate speed over rough terrain?
    - External sound – How will the operator detect the sound of other vehicles moving or weapons firing in his vicinity?
    - Traction – How will the operator be able to judge the trafficability of a piece of terrain without being able to dismount and inspect it on foot?

- Integrated controls – Can control functions be improved to allow better human factors? Can crew workload be reduced and at the same time retain the efficiency of smaller crews? For a combat vehicle with a two-man crew, what is the division of tasks associated with driving, employment of weapons, and command and control of the vehicle? What do the controls look like? Can they be used efficiently by a tired crew wearing NBC protective gloves and masks?

- Glass cockpits – Can versatile, multi-function displays be made robust enough for a land combat vehicle? Can they be adapted for a variety of lighting conditions? A large temperature range and dirt and contaminants?

- Information and guidance system – Given the implementation of a glass cockpit, as described above, how can the use of visual information instead of oral communication improve the workflow of a tank crew? How can the vast variety of information concerning:

    - The status of the battle field,
    - The precise location of friendly and enemy vehicles,
    - The "structure" of the battle space from a command and control point of view,

  be integrated into the information display elements of the vehicle?

- Engine and drivetrain controls – Can powertrain controls be developed to achieve fuel efficiency sufficient to operate for up to a week without refueling? Can traction control of a distributed powertrain be developed with enough efficiency to allow a wheeled vehicle to perform missions now performed by tracked vehicles?

- Fuel and ammunition management – Can a control be developed to accurately measure the fuel consumption of a vehicle which is not topped off every day? Can a system be developed to maintain an accurate inventory of on-board ammunition (including non-ready munitions stored outside the magazine)

- Automated replenishment – Can a system be developed to allow an unmanned logistic re-supply vehicle to find its intended customers, dock with them, and automatically replenish fuel, ammunition, food, and other expendables, and return to base without human intervention?

- Power management of hybrid vehicles – Can a control system be developed to efficiently manage power generation from a primary power supply, regenerated power from braking, NBC air purification, crew environmental control (heating, air conditioning, dehumidification), and battery charging without attention from the crew?

4.3 CONTROL OF AIR VEHICLES

4.3.1 General

Aircraft operational requirements, are defined by the customer (airforce, army, navy or marine), in order to effectively fulfil the military missions which in turn determine design requirements for the flight control system. A typical mission might be constructed from a combination of the following elements for which task-tailored control modes might be designed to reduce pilot workload and to maximise the mission effectiveness:

- taxiing
- take-off (conventional/short/vertical/catapult launch
- acceleration and climb
- reconnaissance
- air-air combat manoeuvring
- close formation flying
- in-flight refuelling
- terrain following
- ground attack
- descent and landing approach
- landing (conventional/short/vertical/arrested shipboard)

4.3.2 Definition of Frames of Reference

Aircraft reference systems are almost always body-fixed co-ordinate systems. This can be either body axis with the x-axis aligned with the aircraft longitudinal axis, or a stability axis system with the x-axis aligned with the steady-state velocity vector. Roll is defined as a rotation about the x-axis. Yaw is defined as rotation about the z-axis, an axis perpendicular to the x- and y-axes, forming a right-hand rule system and consequently pointing out of the bottom of the aircraft. Use of a body-fixed system avoids having to re-calculate moments and products of inertia as the vehicle rotates.

4.3.3 Objectives of Aircraft Control

The objectives of (military) aircraft control are:

- To maintain stability; especially for modern fighters, some of which are designed to be naturally unstable for performance reasons and need a flight control system to provide artificial stability.
- To follow a prescribed trajectory
- To perform missions whereby high-precision control of the vehicle is required, such as during in-flight refuelling procedures, bombing manoeuvres, low level terrain following and during formation flying.
- To fly complex manoeuvres, for example attack manoeuvres.
- To optimise performance for example with respect to time or fuel efficiency.
- To prevent air vehicles from entering a dangerous or uncontrollable flight regime, for instance at high angles of attack or in flutter domain.
- To provide satisfactory flying qualities across the whole flight envelope

All aircraft have six degrees of freedom in flight, three rotations and three translations. The operating margins are defined in the flight envelope in terms of speed and load factor limits that are functions of altitude and aircraft configuration (see Figure 2.12, Section 2.4.2).

Generally, air vehicles, of which aircraft make up the larger portion, can be divided into a number of categories. The most important and relevant for military operations are:

- Fixed wing aircraft
- Rotary wing aircraft, ie helicopters
- Unconventional aircraft designs such as Short Take-Off Vertical Landing aircraft, tilt rotor or tilt wing aircraft

Other air vehicles include air ships and gyroplanes but these will not be discussed in detail here as they are not, or only sparsely, used for military applications.

Fixed wing military aircraft can also be subdivided into low manoeuvrable and medium or highly manoeuvrable categories. This is approximately equivalent to the division between tanker, transport and large aircraft which are usually manned by several crew members, and attack/fighter type aircraft, which are typically operated by a single or dual crew. It is obvious that more stringent requirements usually apply to the control of single seat aircraft, in which the pilot has the additional task of operating non-flight related systems. In this respect, USAF flying quality requirements classify an aircraft in the following classes, which are functions of the mission to be completed:

- Class I, small light aircraft, e.g. light utility aircraft
- Class II, Medium weight, low-to-medium manoeuvrability aircraft, e.g. light/medium transport or heavy attack aircraft
- Class III, Large, heavy low-to-medium manoeuvrability aircraft, e.g. heavy transport aircraft
- Class IV, High manoeuvrability aircraft, e.g. fighters

The above classification provides a division into handling qualities requirements that aircraft have to meet for the different phases of flight during a mission. These requirements will be more or less stringent depending on the type of mission and configuration. All aircraft, regardless of class, are required to possess Level 1 handling qualities for normal states (i. e. no failures) in the Operational Flight Envelope (OFE). Level 2 or Level 3 handling qualities are allowed outside the OFE or for failure cases. Some quantitative requirements are different between the aircraft classes because of the piloting tasks required of them. The requirements are usually more stringent for Class IV aircraft because their tasks are dynamically more demanding.

Air vehicle control effectors are required to control the vehicle attitude in pitch, roll and yaw by generating forces and moments, either conventionally by aerodynamic means or by other means, e.g. using thrust derived from the engine:

- Aerodynamic controls (fixed wing aircraft, STOVL aircraft in normal flight, rotorcraft)
- Control thrusters (STOVL aircraft in transition and hovering flight)
- Vectoring nozzles for increased control power, particularly for fighter aircraft

4.3.4 Control Effectors

Figure 4.8 provides an overview of the typical layout of the aerodynamic controls on an aircraft.

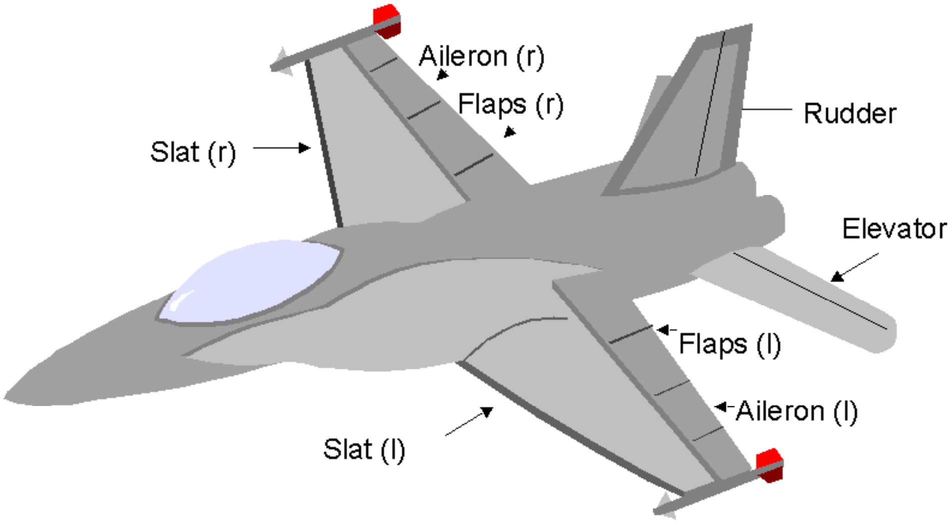

Figure 4.8: Layout of conventional aerodynamic controls on an aircraft

Manual control of modern aircraft generally requires additional augmentation provided by the flight control system. The pilot usually has one of the following cockpit configurations:

- Yoke or stick, rudder pedals and throttle, the usual layout for conventional fixed wing aircraft with aerodynamic controls
- Power or thrust controls to control engine speed or power output
- Throttle control lever, which regulates the engine power output
- Propeller control lever, to control the propeller rpm
- Collective controls on a rotary wing aircraft.

In addition to flight control inputs, the manual inceptors (stick, yoke or throttle) are usually equipped with additional knobs and selectors to allow certain system actions or selections without the need to release controls. This concept (Hands-On-Throttle-And-Stick or HOTAS) is usually implemented in modern fighter/attack aircraft. AGARD (1996), provides numerous examples of cockpit layouts, HOTAS configurations and control approaches for modern military and civil aircraft.

4.3.5 Fixed wing aircraft control

The attitude of a fixed wing aircraft is controlled either manually by the human pilot (whether or not assisted by augmentation systems) or by an autopilot.

4.3.5.1 Manual Control

For primary manual control the following control manipulators are available: a control stick or control column/ wheel, pedals and throttle(s).

For **primary** control of an aircraft, the following control effectors are generally available:

- *Elevator* or *stabiliser* for pitch control, which may indirectly control flight path or speed
- *Throttle(s)* for speed axis control or flight path control for V/STOL configurations
- *Ailerons*, whether or not in combination with spoilers and differential tail, for roll control. These may be the primary means for controlling the direction of the aircraft coordinated with elevator and rudder, although it becomes mostly elevator control in high banked (high-g) turns
- *Rudder*, for yaw control.

Secondary controls may include:

- *Flaps* and *slats*, which are used to enable reduced landing speeds, and secondly to improve the manoeuvrability of the aircraft during sharp turns and combat. In a typical modern combat aircraft, the deflection of flaps and slats is performed automatically by the fly-by-wire control system. On the other hand, in transport type aircraft the flap deflection is still controlled manually using fixed detents since these controls have a great impact on performance and manoeuvrability.
- *Gear selector*, which is used to retract or extend the aircraft undercarriage. Irrespective of the level of automation onboard the aircraft, undercarriage selection is always performed manually.
- *Speed brake*, which is used to increase aerodynamic drag for more rapid deceleration or increased rate of descent for various applications during flight, e.g. configuration for approach and landing.
- *Transfer of mass*, typically transfer of fuel, in order for instance to modify stability margin and improve stability or performance of the aircraft configuration with respect to flight conditions

The control surfaces of modern aircraft are generally operated by hydraulic or electrical actuator systems, which may be required to overcome large hinge moments that arise when theses surfaces are deflected. To provide kinaesthetic cueing to the pilot, most fixed wing aircraft use an artificial force-feel system. This system maintains the classical relationships such as stick force per “g” and longitudinal stick force stability even if the true dynamics of the aircraft do not generate these relationships.

Typically, force-feel systems require the pilot to push the control column to lower the aircraft nose, and hence speed up, and to pull the control column to raise the nose and hence slow down, all in the absence of throttle movement. Trim systems are provided to relieve this force requirement over the long term, allowing hands-off stabilised flight.

4.3.5.2 Stability Augmentation and Autopilot Control

To assist the pilot in his primary tasks of stabilisation and control, aircraft are frequently equipped with an autopilot. The primary task of an autopilot system is to maintain a stabilised attitude in pitch and roll, particularly in the presence of atmospheric disturbances. Moreover an autopilot allows the pilot to select (and maintain) a particular altitude or heading, or to follow a prescribed ground track to navigate the desired route. More advanced autopilot functions may include the ability to execute an automatic approach and optional landing or even low-level terrain following.

4.3.5.3 Engine Power Control

The power or thrust supplied by the aircraft engine(s) is controlled by the thrust lever(s). Speed is primarily controlled by the throttles which are set either manually or by an autothrottle system. The autothrottle maintains aircraft speed at a selected value during normal flight or automatically sets and maintains a given thrust during take-off, climb or descent.

- By selecting a particular throttle setting, the (auto)pilot is able to control the energy rate of the aircraft. The aircraft’s energy is in turn divided between kinetic energy (velocity) and potential energy (altitude), depending on the aircraft’s attitude.
- In the case of a propeller driven aircraft an additional control lever is usually installed which controls the propeller rpm, which is usually varied depending on the power setting of the engines during flight.

4.3.6 Rotorcraft Control

Unlike fixed wing aircraft, most rotorcraft do not rely on fixed aerodynamic surfaces in an uniform flow to provide the primary aerodynamic forces and moments for control, although many do have horizontal and vertical stabilizers which augment other, more primary, sources of aerodynamic forces and moments. The main source of control forces and moments for a rotorcraft is a system that alters the angle of attack of the rotating main rotor blades in a uniform (collective) or distributed (cyclic) fashion to develop pitching and rolling moments and vertical force. Control in the yaw axis is provided by either a collective pitch control of a tail rotor element, which may or may not be shrouded, or by other aerodynamic schemes. The most notable "other aerodynamic scheme" is the NOTAR (No Tail Rotor) in which air enters an intake and is driven into the tail boom by a high-speed fan. This airflow exits through a pair of fixed slots in the side of the tail boom, which, by coupling with the predominately downward flow induced by the main rotor, produces "Coanda Effect" and thus an aerodynamic force in the horizontal plane. In addition, there is a nozzle at the end of the pressurized boom to allow further yawing moment to be produced at the command of the pilot. With twin rotor helicopters, a system that distributes the torque applied to the two rotors is used to control the yaw axis.

In addition to this basic control, systems are often installed which may provide:

- Stability augmentation (SAS)
- Stability and Control Augmentation Systems (SCAS)
- Attitude hold
- Altitude hold (radar or barometric altitude, or using sonar buoy depth)
- Automatic transition to hover, horizontal position hold, during hover

4.3.7 V/STOL (Vertical/Short Takeoff and Landing) Aircraft

These aircraft represent the special case of fixed-wing aircraft operating at low to zero airspeeds during takeoff and landing. In this regime, STOL aircraft typically operate on the backside of the power curve; that is, to slow down, more power is required. In this domain, the classical short period and phugoid modes coalesce to produce unconventional response dynamics. Modern aircraft in this class have stability and control augmentation to produce satisfactory handling qualities. Although the aircraft handling qualities could be augmented to give the pilot front side of the power curve characteristics, the preferred choice for hover and low-speed flight seems to be good back side characteristics. This means that the throttle controls flight path and pitch attitude controls speed, with minimum coupling between the axes.

Figure 4.9 - Harrier STOVL aircraft maintaining attitude control in hovering flight using control thrusters

Aircraft with a vertical flight or hover capability, such as the Harrier in Figure 4.9, require controls other than the conventional aerodynamic control surfaces. These additional controls involve vectored thrust or reaction controls powered by air bled from the engine. These aircraft typically use special control modes, such as forward and lateral position command, or velocity command. This reduces the pilot workload for precision hovering and very low speed maneuvering. These control modes are blended through a transition speed range into conventional control for up-and-away flight.

4.3.8 Ground Effect as a Special Task

An aircraft flying in close proximity to the ground experiences changes in the aerodynamic characteristics that can be very significant. Conventional aircraft on landing typically experience a benign cushioning effect that aids the flare. This effect can be adequately predicted from wind tunnel tests. There have been many problems, however, with the unexpected interference of power on ground effects, i.e. for a V/STOL aircraft. The AV-8 Harrier originally had a suckdown effect when hovering close to the ground, amounting to a loss of vertical lift. This was eliminated with Lift Improvement Devices, fences on the underside of the fuselage, that channeled the engine exhaust recirculation flow to prevent low pressure regions under the wings. [GARTEUR (2002)] Powered lift STOL aircraft have also encountered ground effects that did not agree with wind tunnel predictions. For the YC-15 externally-blown flap STOL aircraft, flight test results indicated that a normal, very positive, ground effect was present and the predictions of suckdown were incorrect in practice [Wood *et al.* (1977)]. Another similar effect was encountered on the STOL & Maneuver Technology Demonstration Program, [Moorhouse *et al*. (1993)]. To achieve short landing distances, this research aircraft landed with thrust reversers deployed. Static wind tunnel tests predicted a significant nose-up pitching moment at touchdown, so the control laws were designed to mitigate this ‘problem’. The first flight test landing indicated a strong pitch nose down, and the ground effect at touchdown was determined to be equal and opposite to the wind tunnel measurements. The reference also presents a discussion of a late wind tunnel test with a moving model approaching a ground plane. This test more nearly replicated the dynamics of landing and gave an excellent correlation with the actual ground effects. The underlying message is that ground effects on any vehicle that depends on powered lift require special attention.

4.3.9 Control of Unmanned Air Vehicles (UAV)

The control elements of UAVs are the same in most respects as for their larger scale, fixed or rotary wing counterparts. Salient differences do exist, however, in the level of augmentation employed and the level of autonomy embodied in the control system. A significant number of these vehicles are autonomous at a very high level (i.e., the operator defines the flight route and the vehicle then performs the mission with minimal interaction with the operator). In these cases, the robustness of the overall control system is exceedingly important. . As an example, if communication with the operator is interrupted, the vehicle must continue or go into a safe holding pattern.

4.4 CONTROL OF SEA DOMAIN VEHICLES

4.4.1 General

A defining characteristic of marine navigation and manoeuvring is that the functions of speed control and directional control are not integrated. For surface ships, there is no direct relationship between speed and direction, and generally only a weak one between speed and rate of change of direction; e.g., there will be some speed loss in a turn at constant rpm. However, there is a significant indirect relationship between speed and direction in the presence of external environmental disturbances, since the latter, and the ship’s responses, are invariably strongly directional. Figure 2.13 in section 2.4.3 illustrates how warship operability in a seaway may require reduced speed to maintain a heading, or a change of heading to maintain speed (e.g., to ensure sufficient control authority). A block diagram showing the classic ship manoeuvring control system is depicted in figure 4.10. As mentioned previously, this diagram concerns heading control only, not speed.

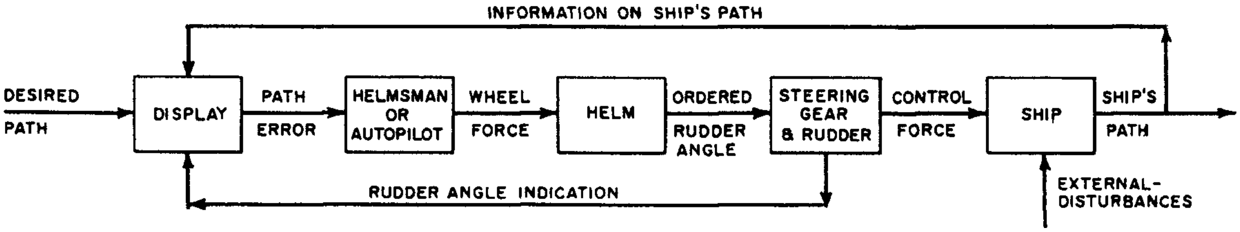

Figure 4.10 - Classic ship manoeuvring control block diagram (from Lewis (1988)).

Submarine manoeuvering in the horizontal plane has similar characteristics, but manoeuvering (and hence control) in the vertical plane is complicated by the hydrostatic pitch restoring moment, as noted below.

Manning levels on all but the smallest vessels have in the past been such that control of speed and direction has involved separate operators at different consoles, although overall command and coordination has always been centralized on a single individual. More recently, reduced manning and a higher degree of system automation have resulted in the consolidation of these, and some other functions, in fewer, semiautomatic, control stations. In naval craft, combat and communication systems remain independent and separately-manned functions. The central command in general receives information from, and with few exceptions controls, all these systems through subordinate operators, rather than directly. So, for example, the sighting problem is the responsibility of a subordinate operator or team of operators.

Major weapon systems, such as submarine torpedoes and missiles, are of necessity tightly integrated with both the platform, its sensors, and sensors on other platforms (e.g., for integrated battle group air defence as proposed in the US CEC). Nevertheless, manoeuvring control remains a separate function from weapon control except through the operator at the highest command level.

4.4.2 Definitions

In order to have a common understanding of terms relating to ship manoeuvrability in both the hydrodynamic and control communities, this section will define most of the terms used. Additional definitions of ship controllability and stability are given in Lewis (1988).

4.4.2.1 Controllability

Controllability encompasses all aspects of controlling a ship's trajectory, speed, and orientation, at sea as well as in restricted waters where positioning and station-keeping are of particular concern. Controllability is usually divided into three distinct areas or functions:

- Course-keeping: the maintenance of a steady mean course or heading. Interest centers on the ease with which the ship can be held on course.

- Manoeuvring: the controlled change in the direction of motion (and depth in the case of underwater vehicles). Interest centers on the ease with which change can be accomplished and the radius and distance required to accomplish the change.

- Speed changing: the controlled change in speed including stopping and backing. Interest centers on the ease, rapidity and distance covered in accomplishing changes.

4.4.2.2 Open and Closed-Loop Stability

In vehicle dynamics, stability is conventionally a measure of the response to a small disturbance. For marine vehicles it is common to distinguish between open-loop (uncontrolled) and closed-loop (controlled) stability. When there is no corrective action from a helmsman or autopilot the control loop is open, otherwise when there is action to correct the ship's position or heading the control loop is closed. For surface ships, three different types of stability can be identified:

- Open loop straight line stability: an uncontrolled ship moving straight ahead has straight line stability if its path is straight, but on a different heading, following a disturbance in yaw. (Since, neglecting wind forces, there is no restoring moment for a change of heading, this is the only mode of open loop stability possible.) This mode of stability is determined experimentally by the spiral manoeuvre, see Figure 3.9. For agile closed loop manoeuvering, a marginal degree of open loop instability may be permitted.

- Closed loop directional stability: a controlled ship returns to the same heading, but a parallel path, following a disturbance in yaw. This is the minimum requirement for controllability in open water.

- Closed loop positional stability: a controlled ship returns to the same path following a disturbance in yaw. The ability to achieve this rapidly is a basic requirement for controllability in confined water.

For underwater vehicles, the same definitions apply to manoeuvering in the horizontal plane. However, in the vertical plane there is invariably a hydrostatic restoring moment in pitch because of vertical separation of the centers of buoyancy and gravity, so at low speed there is invariably "metacentric" (directional) stability. At a high enough speed, the restoring moment is negligible, and stability characteristics are similar to the horizontal plane. If the vessel is stable at high speed, then it is unconditionally stable at all speeds. If not, there is an intermediate critical speed at which the vertical plane dynamics change from stable to unstable.

While submarines and other underwater vehicles may be permitted a degree of instability in the horizontal plane, catastrophic consequences of depth excursions outside the operating envelope generally require adequate vertical plane open loop stability. For the same reason, positional stability, i.e., return to initial depth, is required for safe manoeuvering under closed loop control; furthermore, the response must be both rapid and well damped.

4.4.2.3 Manoeuvrability

Manoeuvrability is defined as the capability of the ship to carry out specific manoeuvres. Excessive straight-line stability implies that the ship will be unresponsive to the effectors (rudder(s) etc.), whereas a ship with marginal straight-line stability is quite sensitive to small control corrections. Thus a compromise between straight-line stability and manoeuvrability must be made.

4.4.3 Ship control system

This subsection is largely derived from draft working papers produced by the NATO Naval Armaments Group (NG6) Specialist Team Naval Ship Manoeuvrability, ST-NSN. Typical generic naval ship automatic manoeuvring system is presented in Figure 4.11. It consists of three major modules, the guidance system, control system and navigation system.

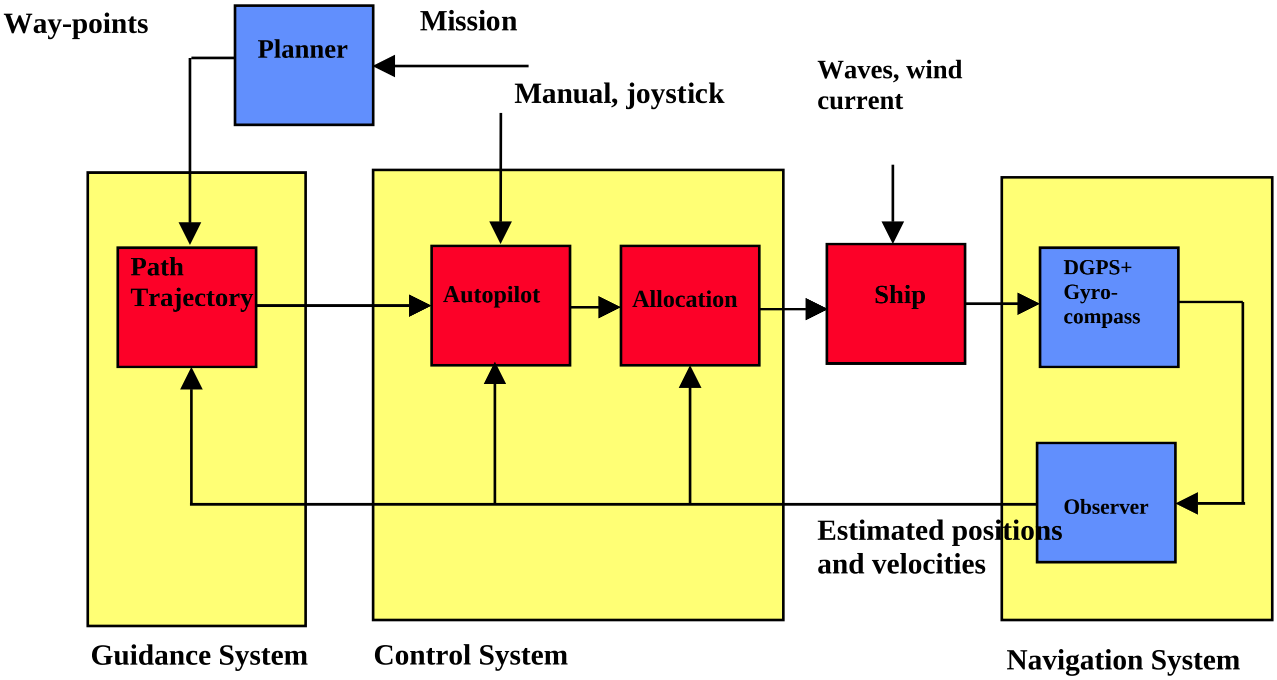

Figure 4.11 - Block diagram of a generic ship manouevring control system

4.4.3.1 Guidance System

The guidance system provides smooth and feasible set points or time varying references to the control system based on the actual mission, weather condition and other parameters. Traditional course-keeping autopilots use the course setpoints as reference. With the advent of the GPS-technology, another control strategy is to control the ship's position (latitude and longitude) instead of the heading. The reference is then either the desired path or the cross-track error, which is the distance from a desired line between two way-points.

4.4.3.2 Control System

The control system defines all necessary equipment, both hardware and software to derive control signals to the ship's propulsion and steering system. The controller may be either a human operator or an autopilot. Based on the references and setpoints, and the actual state of the ship, the controller determines appropriate rpm and rudder commands. For a ship equipped with more than one rudder and one propeller, or with multiple thrusters, the controller commands must be distributed to several control units. The thrust allocation is an algorithm transforming a desired force and moment to different control units based on some criterion, e.g., best manoeuvrability or minimum use of power.

4.4.3.3 Navigation System

The navigation system is defined as both the hardware and software for estimating the positions and velocities required for accurate control. Normal instrumentation for a ship control system is a GPS receiver and a gyrocompass. In order to remove the first order wave motion from entering the control loop, an observer or filter is used to generate estimates of the positions and velocities.

4.4.3.4 Fully Actuated and Underactuated control

In order to independently control ship motion in surge, sway, and yaw, at least three separate control units have to be used. For example, for a ship equipped with two podded thruster units (see figure 4.12(l)), so that two thrust vectors can be controlled, it is (in principle) possible to control surge, sway and yaw independently. This control strategy is denoted fully actuated or actuated. Otherwise, for a ship with the classic arrangement of only one propeller and rudder, it is not possible to control the three degrees of freedom independently, and this is denoted underactuated control; i.e., with only two control units available, there is a degradation of controllability.

4.4.4 Surface Vessel Control

The standard arrangement for control in the horizontal plane is one or more rudders located aft of one or more propellers at the stern of the ship. However, there are many variations on this (see, for example, Lewis (1988) and SNAME (1993)), as well as vectored thrusters that may augment or replace the conventional steering and propulsion systems. A number of steering and propulsion arrangements for surface ships are sketched in figure 4.12. There are also numerous other devices including pumpjets (fixed or steerable), Kitchen rudders, paddlewheels, and contra-rotating propellers. Specialized fast shallow-water craft such as ACVs may employ air propellers for propulsion; these may be steerable, ducted, and can be used with marine or air rudders (the latter in the propeller wake).

Control problems encountered with the standard rudder/propeller combination include loss of rudder effectiveness in heavy, especially stern, seas. Despite that, and the aspect of underactuated control, this arrangement remains the most economical and efficient for most surface ships.

Fully-submerged hydrofoils are inherently unstable in lift (apart from a small degree of very-near-surface stability that is rarely exploited), so require active automatic controls to maintain height above the surface. Surface-piercing hydrofoils are passively stable but active lift augmentation is often used to alleviate the problems of operating in a seaway.

Conventional surface ships may also use active fins for reduction of roll, heave, and pitch motions. (SWATH vessels invariably incorporate active fins because of their low hydrostatic vertical restoring force.) With suitably modified steering gear, it is feasible to use conventional rudders for roll stabilization. Flume tanks, sometimes actively controlled, are also used for roll stabilization. These requirements, while not addressing manoeuverability directly, may nevertheless significantly impact manoeuvering and will add another level of complexity to overall vehicle control.

4.4.5 Maritime Manoeuvring

All water-borne vessels share some fundamental requirements for manoeuvring:

- Slipping or leaving a berth or buoy; weighing an anchor
- Berthing alongside or picking up a buoy; or anchoring
- Negotiating confined waters
- General passage to and from a destination

Warships require more precise control for a variety of evolutions, for example:

- Mine warfare – in particular the ability to hover whilst hunting
- Replenishment at sea in close proximity to one another with dissimilar sized ships
- Launching and recovering fixed and rotary wing aircraft
- Amphibious beach assaults
- Manoeuvring whilst under attack but still providing a stable weapon platform
- Ceremonial occasions

In the past, the provision of harbour tugs for warships and supply vessels has generally not presented a difficulty or an evident cost. However, recent emphasis on through life cost management together with the geographic constraints of some harbours and the non-availability of tugs in some parts of the world, has required revision to new build criteria. That is, bow thrusters are now being specified for larger vessels to enable them to be self sufficient in confined waters and to berth in winds of up to 20kts.

Merchant ships too have special manoeuvring requirements, for example;

- Harbour or salvage tugs
- Geo-stationary positioning for oil exploration drilling rigs
- Re-supply/maintenance vessels operating amongst oil exploration and extraction rigs
- Roll-on/Roll-off ferries
- Lifeboats providing coastal rescue services

The manoeuvrability of merchant ships is well documented in IMO publications, see Chapter 5 of this report.

4.4.5.1 Shallow Water Effects

Boats and ships are significantly affected by shallow water. Because of the Bernoulli effect, flow around the hull accelerates due to the proximity of the bottom of the hull to the seabed. The increase in velocity results in a higher drag comparable to this higher effective speed. In addition, the accelerated flow will pull the vessel down (known as sinkage or squat), causing the ship to act as if it had a larger displacement. When shallow water causes speed loss, and by how much, can be predicted with reasonable accuracy by the widely-used Schlichting method.

In this method, speed loss is a function of the ratio $\sqrt{A_x}/h$, where A_x is the hull maximum cross-sectional area and h is the shallow water depth, and of the depth Froude number, $F_{nh} = V_\infty/\sqrt{gh}$, where V_∞ is the ship speed in water of infinite depth and g the gravitational constant; see figure 4.13.

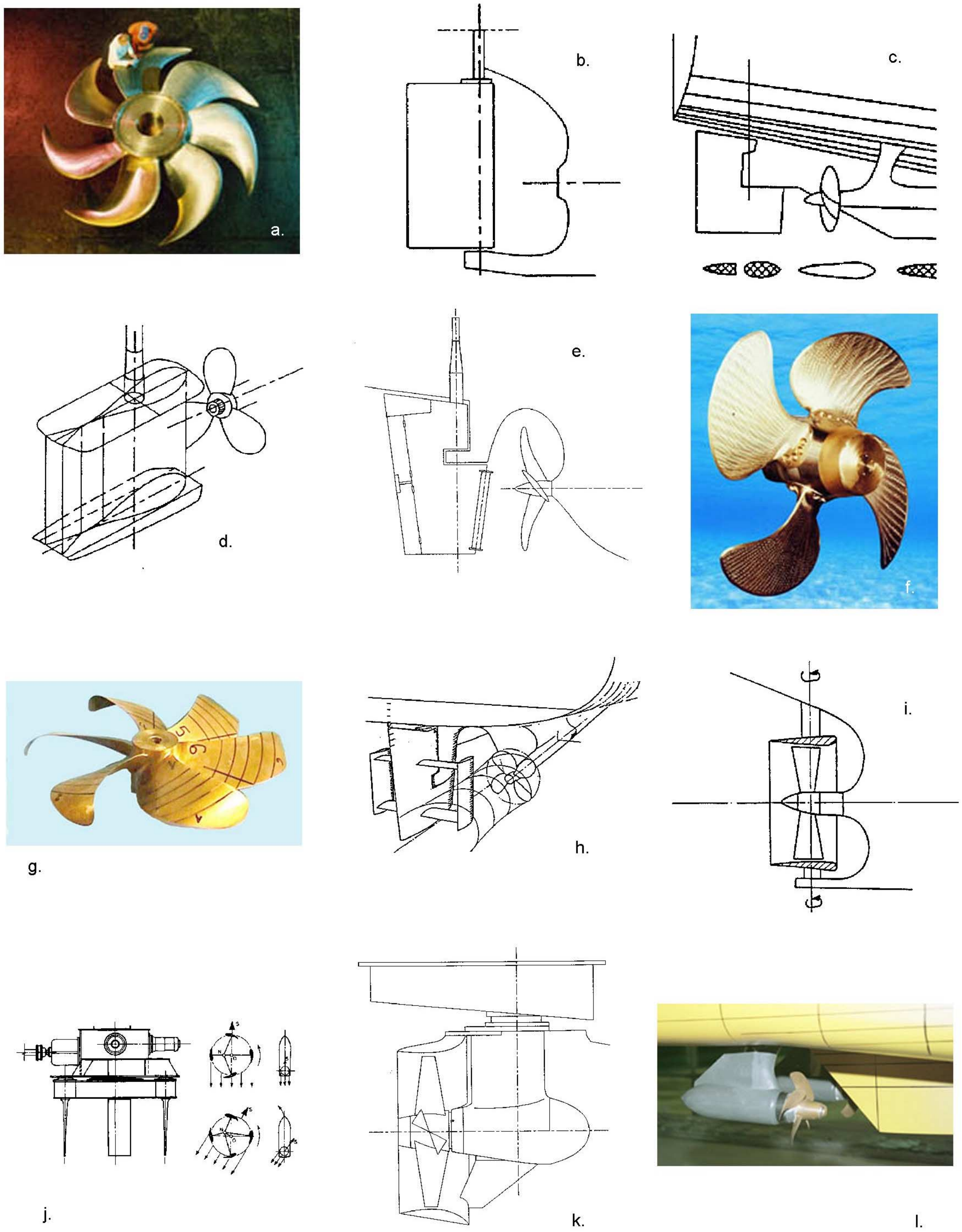

Figure 4.12 - Ship propulsion and steering: a. fixed pitch, high sweep propeller; b. balanced rudder, single screw; c. semi-balanced, twin screw; d. Schilling rudder; e. skeg rudder with flaps and l.e. cylinder; f. controllable pitch (CPP); g. Kappel winglets; h. outriggers; i. steerable Kort nozzle; j. vertical axis propeller; k. Z-drive thruster; l. podded thruster.

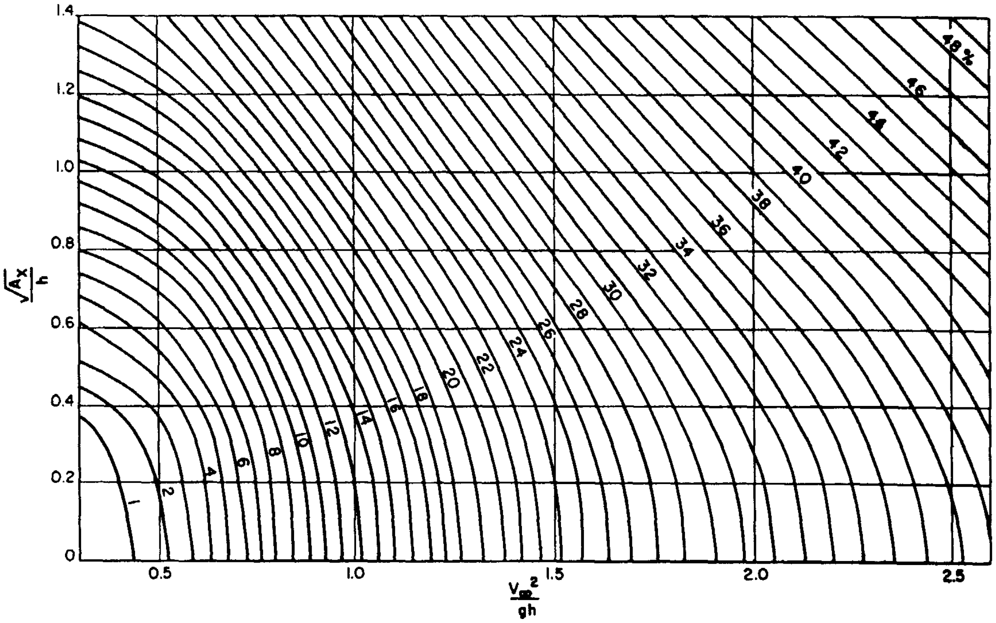

Figure 4.13 - Schlichting's chart for calculating speed reduction in shallow water. The contours give speed loss as a percentage of V_∞. (From Lewis (1988).)

There is typically no measurable speed loss as long as F_{nh} is less than about 0.4. As the water depth decreases so too does vessel speed. The water need not be all that shallow, particularly at higher speeds with larger ships. Whereas the effect of squat is not a new problem, areas in the world that were once considered relatively deep are now comparatively shallow for new, large deep draught vessels. Speed loss is further increased in confined, shallow water.

Squat can cause a vessel to suddenly lose steerageway hence rendering the ship un-manoeuvrable, usually signified by a noticeable sinking of the stern. Control can only be regained by stopping the engines for a period of time and then slowly building up forward motion again. In confined waters, especially with strong tidal streams, this can be an exceptionally hazardous situation.

4.4.6 Control of Submersibles

4.4.6.1 Submarine Manoeuvring Control

Chief concern for submarine manoeuvring is the vertical plane in which depth excursions generally cannot exceed 5 or 6 ship lengths, and may be restricted to less. In addition, operations such as missile launch, communication, and snorting for diesel boats, require a near-surface depth-keeping capability. For horizontal manoeuvres, the asymmetry of the sail will give rise to coupled vertical forces, and rolling and pitching moments — undesirable phenomena at high speed that can, however, be employed to advantage for emergency recovery. (A lively, if at times hysterical, overview of some problems of high speed manoeuvring is given in Gruner and Payne (1992).)

Manoeuvring control is primarily by means of hydraulically deflected control surfaces — sternplanes/rudders, and forward-mounted bowplanes or sailplanes. Typical arrangements are shown in figure 4.14. Planes and rudders have deflection rates of about 5 to 10 deg/s with a range of ±30 deg. This time scale is much shorter than the vehicle response, but considerably greater than that of a human or automatic controller. Time scales of seconds or tens of seconds also apply to propulsion control, and to ballast blowing and shifting for hydrostatic control. Time is critical to emergency recovery; both control time scales and delays in identifying a problem and instituting the recovery procedure are significant factors in the resulting manoeuvre.

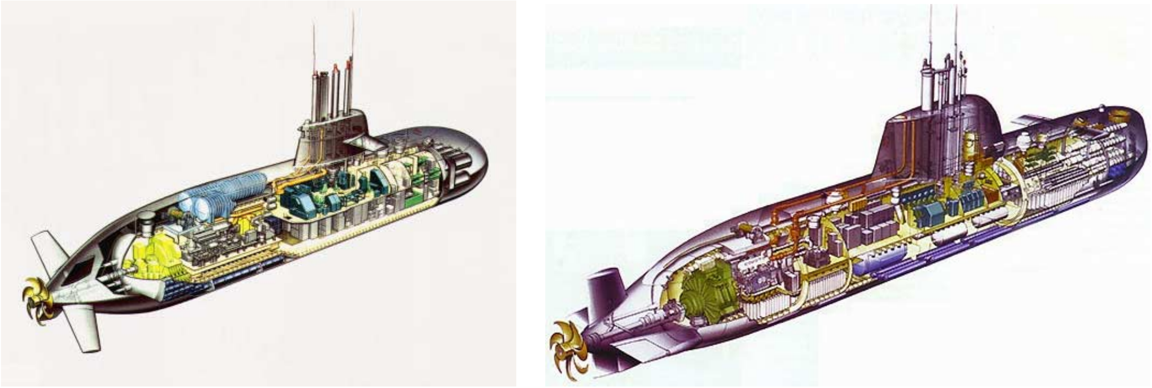

Figure 4.14 - German Type 212 (left) with sailplanes and X-rudders, and Type 214 (right) with bowplanes and a cruciform tail arrangement.

Economic pressure for reduced manning, higher submerged speeds, and use of non-cruciform sternplane/rudder arrangements (to provide some degraded functional capability in case of failure) has accelerated the adoption of automation depth and heading control during routine manoeuvres. Initially, these controllers were stand-alone autopilots using classical control methods. To avoid overshoots, the depth autopilot would typically employ a look-ahead capability based on a phase lead transfer function. Manoeuvring control is now typically based on PD or PID algorithms. At low speeds, tail appendage effectiveness is reduced, eventually leading to control reversal at a critical speed of a few knots. Automatic ballast and trim control is used to augment low speed manoeuvrability, and wave-action compensation may be required for low-speed operation near the surface. The second order low frequency component of wave excitation can be counteracted by enhanced ballast and trim control, but the low rate sensing requirement poses some difficulty. R&D is underway on addressing such problems with neural networks and adaptive filtering methods.

In existing naval submarines (and ships), highest command level integration of manoeuvring, propulsion, and other platform control systems is done by the operating team. Fully automating the process by employing an autopilot to simultaneously manage these systems in order to keep the vessel within its safe operating envelope (Ch. 2, Figure 2.15) has long been resisted because of the catastrophic consequences of failure. However, automatic maintenance of depth and heading is now commonplace, and a higher degree of automatic supervision — e.g., for ballast/trim management at low speed, and for preprogrammed closed-loop manoeuvres such as depth changes — is now generally accepted.

4.4.6.2 Autonomous Unmanned Underwater Vehicles (UUVs)

Autonomous UUVs, which have found widespread civilian application, are now being used for mine countermeasures and other purposes. A notable example was the 180 km out and back mission performed in 1996 by the cable-laying UUV *Theseus* under the ice of the Canadian Arctic (Verrall and Butler (1999) and figure 4.15.). The navigation/control system included fault management using a predetermined response table.

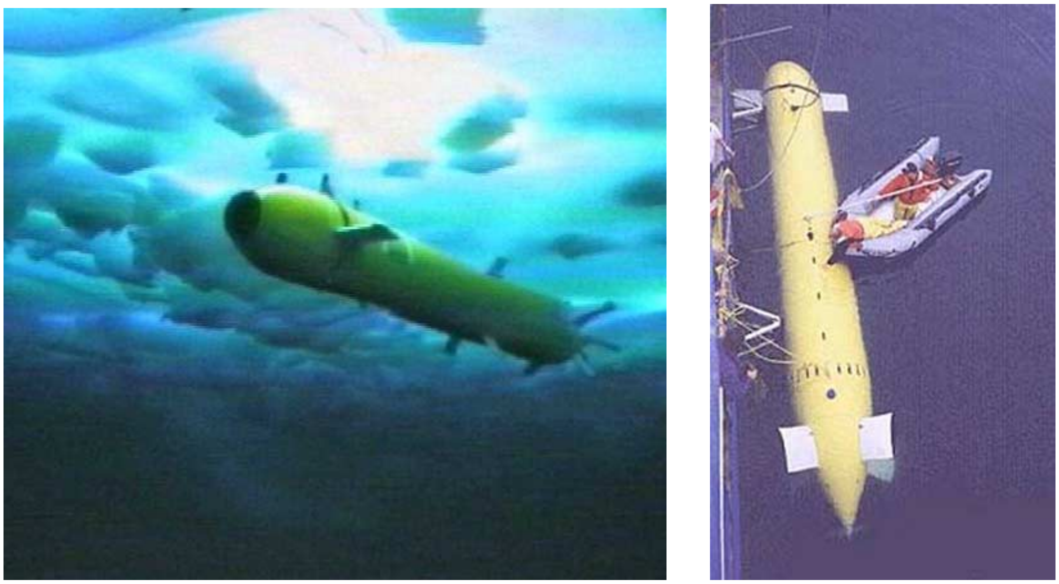

Figure 4.15 - Theseus UUV

Although autonomous UUVs are finding increasing application, Remotely Operated Vehicles (ROVs), figure 4.16, still have an important role where human intervention is required, such as salvage in deep water, and to replace divers for a multitude of tasks at shallow to moderate depth.

ROV manoeuvering and propulsion is generally by means of steerable thrusters (figure 4.16.a and .b). The pilot has to coordinate vehicle motion with operation of the manipulators and other equipment. The mini-ROV shown in figure 4.16.c uses an innovative cycloidal fin system for both propulsion and steering.

The pilot of a ROV has a similar multitask high workload problem as does the pilot of an aircraft, and alleviating it is important. Conventional autopilots for these vehicles have been found difficult to design because their dynamics are strongly coupled, highly nonlinear (with umbilical cable dynamics an additional factor), and variable because configuration can change substantially from mission to mission. Modeling the open-loop dynamics is therefore prone to error; additionally, in closed-loop, there are delays and uncertainties in sensor information. Various adaptive controller schemes have been proposed to solve these problems [Goheen *et al.* (1987)]. Similar issues arise for the control of small manned underwater vehicles, although the problems encountered may not be so severe.

Figure 4.16 - Some representative ROVs: a. deployment; b. USN DeepDrone; c. mini-ROV (Subwave X-fin).

4.4.6.3 Marine Towed Systems

A common example is a bottom-survey system employing side scan sonar installed in a towfish. Typical control objectives are to maintain constant height above the sea floor subject to a maximum rate of depth change, while keeping pitch excursions within narrow limits, and while minimizing pitch rate. Since the towing vessel normally runs at constant speed during a survey (a separate control problem for small towing vessels, given varying tension on the control cable), these objectives are achieved by sensors and control surfaces on the towfish, and in some cases cable-scope control using an active winch.

Figure 4.17 shows a remote mine survey system comprising a semisubmersible autonomous vehicle towing a bottom-profiling towfish with side scan sonar. The mission profile includes transit to operational area with the towfish stowed, towfish deployment, survey of the operational area, towfish recovery, and return transit.

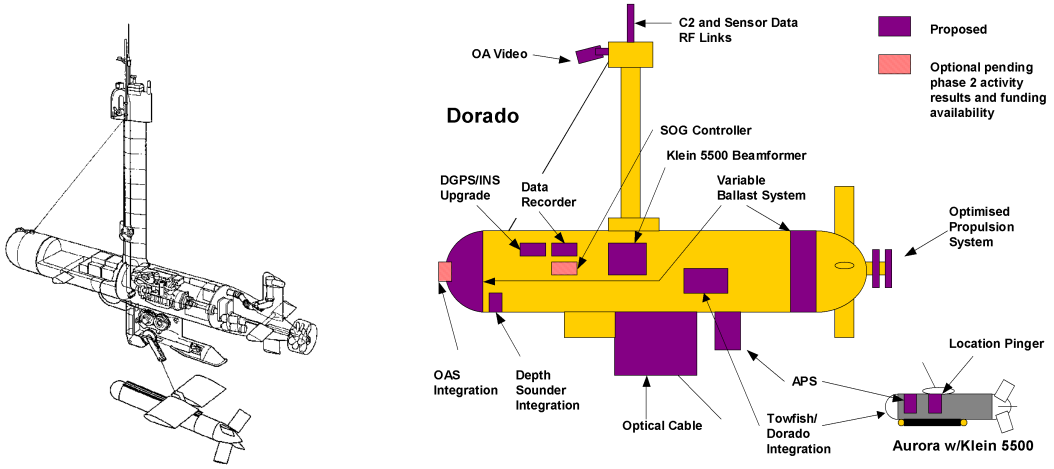

Figure 4.17 - Remote Mine Survey System.

4.5 CONTROL BY WIRE

A technology employed in the control of aircraft is the “Fly-By Wire” (FBW) system. In this situation there is no direct mechanical connection between the pilot inceptors (stick, wheel, levers, etc.) and the control effectors (control surfaces, engines, etc.). The pilot inputs are sensed electronically and processed through a flight control computer. Together with the relevant measured signals that represent the aircraft’s state, this flight control computer (FCC) generates control commands, typically to hydraulic or electric actuation systems that drive aerodynamic surfaces.

FBW can provide artificial augmentation to stabilise a statically unstable aircraft. In high performance fighters this implies that it is no longer necessary to have inherent statically stable bare airframe dynamics. The relaxation of this requirement allows for a much higher degree of manoeuvring agility than can be achieved by statically stable aircraft. Depending on a specific mission task, the response can be adjusted as to make it possible for the pilot to perform a specific task precisely, with a low level of required workload. FBW systems can also be tailored to provide higher bandwidth control, the efficient management of control systems that have redundant control surfaces, and the tailoring of control response dynamics based on flight regime.

The way in which FBW technology evolved from a simple hydraulic booster system towards a full fly-by-wire control system is shown in Figure 4.18. Early aircraft used manual control exclusively. As size, weight and performance increased, aircraft reached a stage where pilots were no longer capable of generating enough force, even with tremendous mechanical advantage, to move the control surfaces precisely and rapidly, so a hydraulically boosted system, much like automotive power steering, was added.

The next major step was to fully powered controls; the mechanical linkage moves only the valves on the hydraulic actuators. The pilot is no longer mechanically connected directly to the control surface and must rely entirely on hydraulic power. In this case, he has to be artificially provided with stick “feel” through such devices as springs, bob weights, etc., which generate the desired handling qualities for the particular type of aircraft. Virtually all modern, high performance military aircraft have fully powered flight control systems.

From power augmentation the next step was to stability augmentation systems (SAS), where feedback of aircraft motion is employed to damp out unwanted motion or oscillations of the aircraft. A control augmentation system (CAS) combines the damping function with electrical feedforward control, allowing the use of higher feedback gain or a more sensitive damper. Adding a clutch, or other means of disconnecting, the mechanical system provides pseudo-FBW; complete removal of the mechanical linkage finally transforms the system into a full FBW control system.

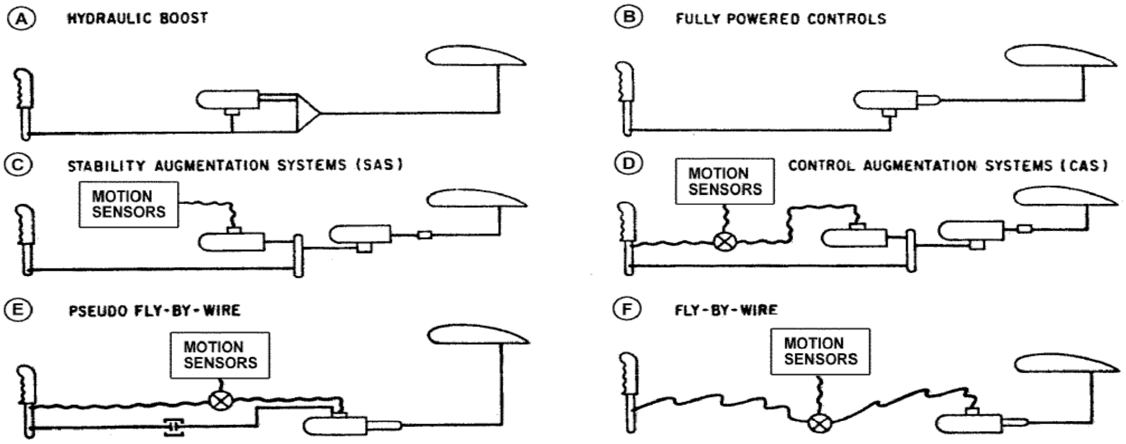

Fig. 4.18 - History of the development of FBW control systems

The benefits obtained from applying FBW technology to military aircraft are:

- it allows for carefree handling by providing angle-of-attack control and angle-of-sideslip suppression which lead to automatic protection against stall and departure, and by the automatic limiting of normal acceleration and roll rate to avoid overstressing of the airframe.
- optimised handling qualities across the flight envelope, and for a wide range of aircraft stores
- aircraft agility, thereby providing a capability for rapid changes in aiming the fuselage or the velocity vector, to enhance both target capture and evasive manoeuvring
- aircraft performance benefits associated with controlling an unstable airframe, that is, improved aerodynamic efficiency (increased lift/drag ratio) and an increase in maximum lift capability, leading to increased aircraft turn capability
- it radically simplifies the use of thrust vectoring to augment or replace aerodynamic control, in order to extend an aircraft’s conventional flight envelope
- reduced drag owing to optimised trim settings of controls, including thrust vectoring
- reconfiguration to allow mission continuation or safe recovery following system failures or battle damage
- advanced autopilots, providing significant reductions in pilot workload and weapon system performance benefits
- reduced maintenance costs, resulting from the reduction in mechanical complexity and the introduction of built-in test

4.6 AIRCRAFT – ACTIVE CONTROL TECHNOLOGY

More and more, in air vehicles, the concept of fly-by-wire is expanded by the use of the term “active control technology”. Early examples of expanded control usage included integrated flight and fire control, integrated flight and propulsion control, etc. Control technology has become so pervasive that the traditional applications have been expanded completely. This concept can be applied to all the vehicle domains. An air vehicle flight control system may include thrust vectoring and many other effectors in addition to controlling the conventional aerodynamic surfaces. The Advanced Vehicle Technology (AVT) Panel of RTO held a symposium in May

2000 devoted to Active Control Technology (ACT) [RTO(2000a)]. The papers covered many topics of active control for a variety of functions. One example was control of the flow field around the vehicle which has been applied to marine vehicles and is being researched extensively for flight vehicles. Another AVT Panel RTO symposium was held May 2001 on Control of Vortex Flow at High Angles of Attack [RTO(2001)]. The various papers presented research results, and also problems that have been encountered in flight test experiments.

Flow control has been used for drag reduction in marine vehicles through the mechanisms of heat, microbubble, and polymer injection into the boundary layer [Moore (1999)]. The most outstanding example of the latter is the series of experiments undertaken with a former-USSR Project 1710 submarine in the 70s [Drunov and Barbanel (1999)]. One motivation for interest in this area is the problem of defence against modern high-speed torpedoes [Vining (2000)]. Antitorpedo torpedoes need to be very fast; with air delivery in the vicinity of the target (e.g., the CIS APR-2E), very short times are available for interception. This has been an area of high research interest for aircraft, where riblets, adaptive shapes and energy injection techniques have been employed. Nevertheless, Bushnell (1997) pointed out that many of these techniques ultimately fail the technological (real-world) filter for adoption (e.g. [Johns (1998)]). An example of, so far, limited adoption is the use of riblets [Bacher and Smith (1986)] for drag reduction. This technique was developed by NASA Langley Research Center, but so far has found its principal application in the marine field, notably in competitive sports [NASA (1993)], an area where the technological filter elements of risk and cost are readily traded off against success.

Another element of active control in the air vehicle domain is reconfigurable control. This requires a real-time system identification algorithm to define the aerodynamic and control characteristics, especially if they change due to failures or battle damage. The control laws are then reconfigured to account for the changes and maintain satisfactory (or the best available) handling qualities. This technology has been demonstrated in research applications, see Binker and Wise (1999).

4.7 AUTOMATIC CONTROL SYSTEMS FOR SHIPS AND SUBMERSIBLES

4.7.1 Ship Autopilots

Effective pneumatic and mechanical servomechanisms for torpedo depth control were developed towards the end of the 19th century. Elmer Sperry constructed the first automatic ship steering mechanism in 1911. The device was referred to as “Metal Mike” and was capturing much of the behaviour of a skilled pilot or a helmsman. Metal Mike compensated for varying sea states using feedback control and automatic gain adjustments. Later, in 1922, Nicholas Minorsky (1885-1970) presented a detailed analysis of a position feedback control system where he formulated a three-term control law, which today is referred as Proportional-Integral-Derivative (PID) control. The three terms in Minorsky’s control law originated from observations of the way in which a helmsman steered a ship.

Modern autopilots using the LQG and the H-infinity control design techniques have been reported in the literature by a large number of authors. Two major control strategies are used:

4.7.1.1 Cross-Tracking

The ship will follow a desired trajectory (generated by the guidance system, for instance) by using way-points. Tracking is performed by minimizing the cross-track error while the forward speed along the desired path can be chosen arbitrarily. This controller is denoted a one degree-of-freedom (1 DOF) controller, since the only control variable is the cross-track error. The desired heading angle is usually chosen tangential to the path or as the angle given by the intersection of the line from the ship to a point located 2 to 3 vehicle lengths ahead, see Figure 4.19. A more advanced concept could be to compute the heading angle by using a minimum energy approach. In the presence of currents, the minimum energy approach implies that the ship's heading angle will be automatically adjusted to a value different from the tangential direction along the path. This is referred to as the inclined or weather optimal heading angle.

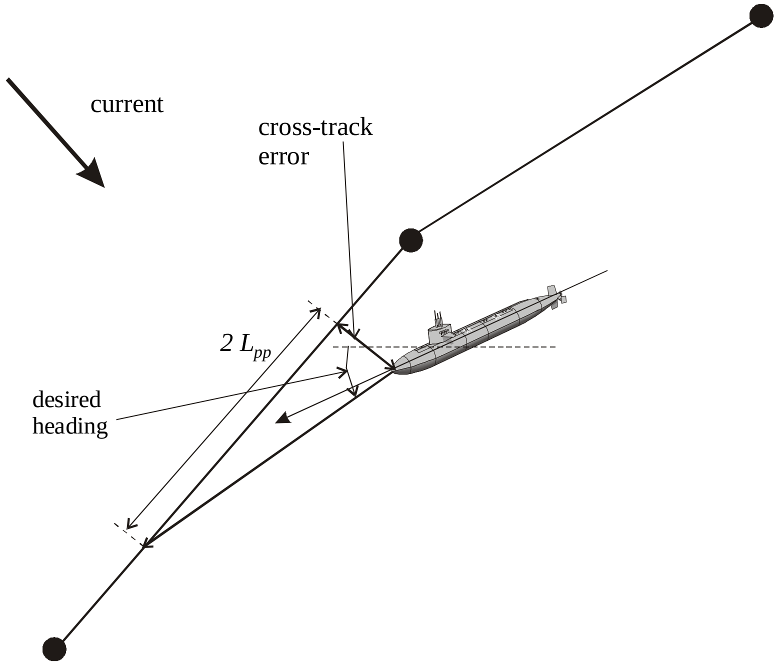

Figure 4.19 - Cross tracking control.

4.7.1.2 Line-Of-Sight (LOS) Tracking

This implies that the ships heading angle is controlled (course-changing autopilot) by using a line-of-sight method to reach the target, see figure 4.20. LOS tracking implies that the heading set-point is adjusted continuously such that the desired angle is the angle between the straight line to the next way-point or the target. This is also a 1 DOF controller, since the only control variable is the heading error. In this implementation, an off-set in the sway position is tolerated.

4.7.1.3 Way-Point Tracking Control

The successful results with LQG controllers in ship autopilots and Dynamic Positioning (DP) systems, and the availability of more precise navigation systems like GPS, have resulted in a growing interest in way-point tracking control. Strategies for controlling one to three DOF can be considered. A 3 DOF way-point tracking controller can control surge, sway and yaw simultaneously. Ignoring the heading loop, a 2 DOF controller may be used to control the ship's position between two way-points ,and the 1 DOF controller implies keeping the cross-track error close to zero.

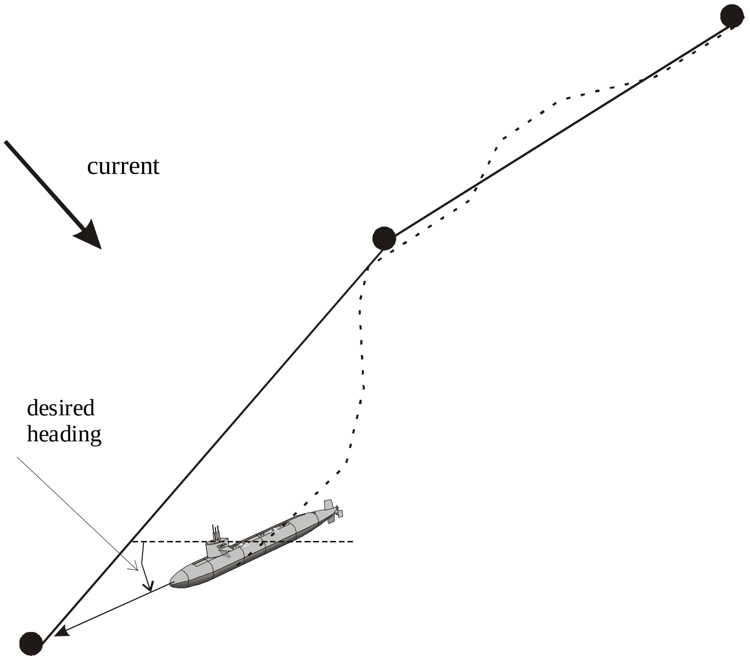

Figure 4.20 - Line of sight tracking control.

4.7.2 Dynamic Positioning

In the 1960s three decoupled PID-controllers were applied to control the horizontal motion of ships (surge, sway and yaw) by means of thrusters and propellers. This was referred to as the dynamic positioning (DP) system. As for the autopilot systems discussed above, a challenging problem was to avoid first order wave induced disturbances entering the feedback loop. Several techniques like notch and low-pass filtering, and dead band techniques were tested for this purpose, but with different levels of success. In 1963, the linear quadratic optimal controller and the Kalman-filter were published by Kalman and his co-authors. This motivated the application of LQG-controllers in ship control, since a state observer (Kalman-filter) could be used to estimate the wave-frequency and the ship low-frequency motions. After 1995, nonlinear PID-control, passive observers and observer backstepping designs have used.

A traditional DP system requires control of both the ship's position and heading; this is 3 DOF control. However, a subclass of dynamic positioning is the weathervaning system. In weathervaning, the ship's position is fixed, but its heading is allowed to vary according to the weather. In an optimal weathervaning system the ship's heading will be pointing against the mean environmental disturbance vector.

4.8 CONTROL SYSTEM DESIGN TECHNIQUES

4.8.1 Applied Control Methods

While the specific implementations of vehicle control systems is as varied as the number of vehicles developed over the years, the control methodology can usually be placed into one of the following categories:

- Classical control techniques, including frequency domain analysis (traditional root locus, etc.)
- Optimum Control, including linear quadratic regulator design

- Robust control, including sliding mode and variable structure
- Rule-based, such as fuzzy logic.

Most of the methods presently in use are generally applied in a domain where the system behaviour is supposed to be linear. As vehicles currently under consideration are highly non-linear systems, especially when pushed to their limits of performance, there is an evident need to develop efficient non-linear methods that can be implemented in actual control system, especially for further extending the maneuvring envelope.

The following provides a very brief review of these various control strategies and shows how various designers have employed them in the development of various vehicles.

4.8.1.1 Frequency Domain Analysis

While there are numerous textbooks and papers that provide discussions on traditional frequency domain analysis, [Friedland (1986)] provides a very clear and detailed examination of this subject. Frequency domain analysis is based on determining the overall transfer function of the closed loop system and then examining the response bandwidth, phase and gain margins, and corner frequencies by looking at things such as the root-locus plot, the nyquist diagram, and the bode plot. Since this is the most traditional method of control system design, there are many examples of systems designed using this technique. Several examples that apply this to underwater vehicle design are the listed papers by Humphreys (1987, 1991, 1992) that describe the control systems for autonomous underwater vehicles and Henderson *et al.*(1989) that employs this technique for developing a controller for a towed vehicle.

4.8.1.2 Optimum Control

Friedland (1986) provides an excellent introduction to control system design using state-space methods, including a detailed discussion on optimum control. Optimum control, in a simple sense, produces a controller that minimizes a specified performance criterion. In the particular example of a linear quadratic regulator (LQR) design, this performance criterion is in the form of an integral of a quadratic expression that includes both the control states (variables describing the vehicles motions) and the control effort (variables that describe the control forces applied to the vehicle). Through careful design of the controller, a balance can be made between the amount of control effort applied to the vehicle and the resulting motions of the vehicle. Hopkin *et al.* (1991) shows how this technique can be applied to an underwater towed vehicle, where it was necessary to maintain minimal pitch motion of the vehicle while maintaining precise vertical tracking. Dreher (1984) and Harris (1984) show how this technique can be extended to provide additional control over the frequency response of the system. This can be particularly useful if the vehicle is subjected to known disturbances of a particular frequency. The resulting control system can be designed to minimize the effects of these disturbances, while at the same time provide a tracking capability.

4.8.1.3 Robust Control

In the early 1980s, it was recognized that particular types of vehicles had very non-linear dynamics and that it was often very difficult to develop accurate hydrodynamic models of the vehicle and the thrusters that were used for control. As a result, new types of controllers were developed to try to compensate for the non-linearities and modeling uncertainties. These controllers were based on a technique known as sliding mode control. Yoerger and Slotine (1985) provides a good introduction of this control strategy, and Yoerger (1986) shows how the technique can be applied to the trajectory control of an underwater vehicle. In simple terms, strategy employs a non-linear switching control law that drives the vehicle state and the state derivative to follow a sliding surface in the state-space plane. It can be shown that the resulting control law can guarantee stability and tracking even in the presence of non-linearities. Healey

(1995), Dougherty and Woolweaver (1990) and Joo-No (1989) also discuss the application of sliding mode control to underwater vehicle design.

In addition to sliding mode control, Appleby *et al.* (1990) describe several other techniques for providing robust control of underwater vehicles. One of these techniques, structured singular value control, is also discussed in further detail in Ruth (1990). A study on the importance of advanced control design methods for the European aircraft industry was carried out in the nineties by the GARTEUR Action Group FM(AG08). The work of this group has been published as lecture notes in control and information sciences [Magni, Bannani, Terlouw (1997)]

4.8.1.4 Rule Based Control

Fuzzy logic is one of the more common rule based control methods. These types of control systems use the rule based structure of expert systems, but add fuzzy set theory to allow for interpolation between set rules. The advantage of fuzzy logic control is that it does not require a detailed model of the process that is to be controlled, and it is very good at controlling highly non-linear processes. A limitation of the technique, however, is that there have to be some basic rules that humans have applied to the system. DeBitetto (1995) describes the application of fuzzy control to the problem of controlling the depth of a submersible through the use of a variable ballast system. Fuzzy logic is used in this particular controller because the process of changing the ballast is a highly non-linear process of blowing and venting air in a flooded tank. In addition, the level of ballast in each tank is not directly measured, but is inferred from the resulting motion and attitude of the vehicle. As a result, this type of system would be very difficult to control with a conventional feedback controller.

4.8.2 Design and Analysis Process Aspects

The design of efficient, robust and highly performing control systems is a subject of intense practical interest. In the case of aircraft control systems, the subject has recently been addressed by an RTO SCI working Group. Their report, entitled “Flight Control Design - Best Practices” [RTO (2000b)], presents various practical lessons learned, from analysis of past problems and from successful designs and shows that some lessons have been re-learned many times. It also shows that there is no correlation between the control design methodology and the various problems that have been encountered. It is postulated that the majority of problems result from the misuse of the design criteria and from unpredicted characteristics, especially non-linearities that were not considered. There are recommendations detailing best practices that should be followed in any future flight control system design. These practices include the use of available design criteria, use of piloted simulation, improvements in project management, etc. There are also discussions of theoretical aspects that can be expected to be outdated by future research.

4.9 SELECTED TECHNICAL CHALLENGES

As illustrated by the breadth of this chapter, vehicle control is a complex and highly changing subject. Each type of vehicle is associated with a unique set of trade-offs. However, given the basic physics, coupled with the human-machine element (to be discussed further in the next chapter), it is clear that vehicle control specialists in all domains share many of the same concerns and competencies.

4.9.1 Multi-Vehicle Control

Aside from single vehicle concerns, additional control challenges can be found in the area of multi-vehicle control. In land systems, automated convoys and leader-follower systems are of particular interest. In the air domain, automated formation flying, particularly in relation to UAV’s is also of concern. Finally, in the ship domain, control systems to improve ship convoys and mine countermeasure systems (MCM) are of great interest. Platooning UUVs for MCM and similar applications has been considered to overcome the limited underwater communication bandwidth [Stilwell and Bishop (2000)].

4.9.2 Technique Challenges

The state of the art in control system design techniques highlights the need for further improvements to deal with:

- The modelling of uncertainty.
- Disturbance rejection.
- Modeling errors.
- Vehicle flexibility aspects.
- Man-in-the-loop (man-machine integration, PIO).

4.9.3 Other Specific Control System Challenges

Specific control system design challenges include:

4.9.3.1 Land Domain:

- Turret stabilization.
- Active suspension systems on land vehicles to cross country speeds.
- Active and independent control of tire inflation pressure, optimized for driving conditions
- Automatic slip control and locking of differentials
- Independent control and distribution of torque at each drive element (wheel or track drive boggie)
- Onboard diagnostics and their integration into the control system
- Redundant control stations

4.9.3.2 Air Domain:

- Carefree manoeuvring
- Improvement of ride quality during low altitude (fighter) operations
- Control of rotorcraft acoustic signature through rotor state control.
- Advanced methods for individual blade control for noise reduction
- Enhanced rotorcraft agility by allowing the pilot to get more out of his vehicle’s performance.
- Integrated control system design for tilt rotor vehicles
- Availability of appropriate sensor suite space, required to develop the control system.
- Integration at different levels of autonomy in the control system, for instance to achieve specific complex missions, for collision avoidance, or in case of cooperative tasks between aircraft and unmanned vehicles.
- Detection of failure and reconfiguration of the control system.

4.9.3.3 Sea Domain:

- Autonomous towed systems requiring precise trajectory control of towed submersibles for mine counter measures.
- Station keeping in rough seas.
- Control of ship’s acoustic signature through independent control of propeller rpm.

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Chapter 5 – Vehicle Performance and Handling Characteristics

5.1 INTRODUCTION

Inherent in manned military vehicles is some performance that enables them to accomplish mission task elements leading to a successful mission. An integral ingredient to the success of these mission task elements is not only the vehicle performance but also the operator and the ease and precision with which the vehicle can be controlled and its performance exploited.

We can paraphrase the definition for handling qualities for aircraft from Cooper and Harper (1969); "Handling qualities are those qualities or characteristics which govern the ease and precision with which an operator is able to perform the tasks required in support of the vehicle role." The same definition can be easily applied to land and sea vehicles where, for example, the operator becomes the tank driver, the ship or the submarine helmsman, or the operating team, taken individually or together. The definition becomes more complicated in many of these scenarios, however, since the operator's direct involvement in the mission success is somewhat inversely related to the size of the vehicle and or the number of people on board the vehicle. For example, it is much more difficult to relate the specific duties of a helmsman of an aircraft carrier in regard to the overall mission success when he is only one of several thousand individuals needed to perform and accomplish the mission. On the other hand, the duties of a pilot of a single-seat aircraft are much more directly linked to mission success. In addition to the comments above, if one considers the operator-team further, one realises that the team environment is conditioned by communication and information flows between members, greatly increasing the potential for error and delay, and subsequently impacting mission performance and levels of compensation required. In all of these various cases, however, one can still consider the vehicle handling qualities, or more simply, the "ease-of-use", as a determining factor for mission success.

It is difficult to define what is a reasonable level of effort and operator skill level when discussing handling qualities. The specification for the Wright Flyer aircraft of 1908-9, required: "It (the aircraft) should be sufficiently simple in its construction and operation to permit an intelligent man to become proficient in its use within a reasonable length of time". Today's specifications, in contrast, are exceptionally more complicated. At both extremes, however, the expectation of acceptable operator skill or competence defines, to some extent, what dynamic characteristics engender satisfactory handling qualities. In general, handling qualities can influence mission success, operator training requirements, crew endurance, and safety.

Figure 5.1 shows a representation of the task-operator-vehicle system including the various components and their influences on each other. This construct begins with the mission or task to be performed and ends with the vehicle-system response. Including stress, the operator must integrate the aural, visual, and motion cues with the task to be performed in manipulating the vehicle controls. These may include not only the principal controls and selectors for the vehicle but also the weapon system and any mission related module controls not directly associated with vehicle control. The vehicle dynamics are characterised by terms such as agility, stability and manoeuvrability, and are impacted by external disturbances. In addition, there may be interaction between the vehicle and weapon system dynamics.

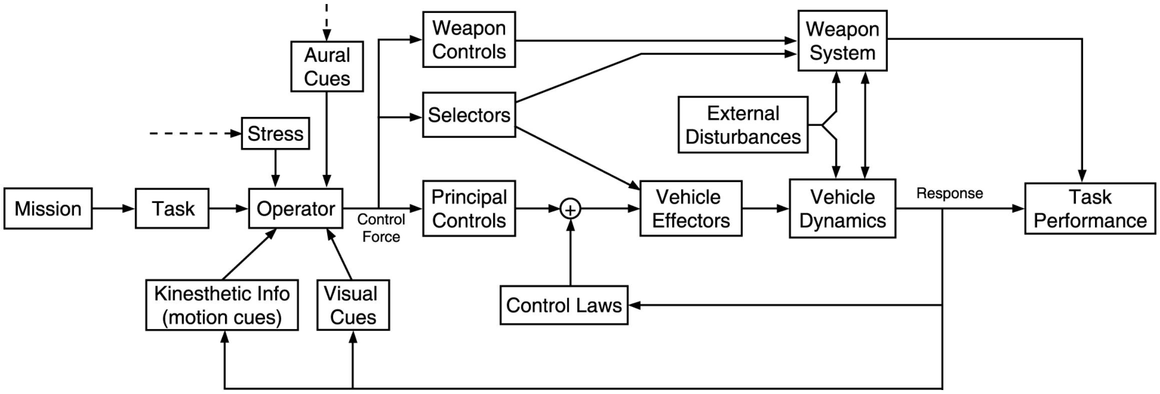

Fig 5.1 - Elements of the Task-Operator-Vehicle control loop that influence handling qualities.

This chapter will describe handling qualities evaluation and criteria development and practices in the land, air, and sea domains. In doing so, it will highlight the similarities and differences between the various domains, and the technical challenges in land, air, and sea.

5.2 HANDLING QUALITIES CRITERIA

Consideration of operator skill level, predictability of response, and the impact of vehicle dynamics on attainable performance demonstrate that handling qualities are important for all classes and domains of vehicles, yet the differences in vocabulary between domain specialists create significant difficulties. However, examination of handling quality criteria suggests that for some aspects of this topic there are fundamental differences between vehicle domains that may reinforce the vocabulary gap.

Handling qualities criteria typically define a set of dynamic response characteristics of the vehicle that influence the operator-mission performance. Examples of criteria for aircraft include defined handling quality levels for the response rise time resulting from a step input, the control system bandwidth, and modal frequencies and damping. Traditionally, these response characteristics are necessary but not sufficient to attain satisfactory handling qualities. That is, if the vehicle violates one of these dynamic requirements, the handling qualities of the vehicle will be degraded. On the other hand, the vehicle may meet all the formal dynamic requirements and still not possess satisfactory handling qualities due to some other phenomena for which there are no criteria.

The development of handling qualities criteria, involves qualitative and quantitative data. Figure 5.2 illustrates the process for an aircraft. Qualitative data require the operator to weigh the level of compensation required to perform a specified task using standardised rating methods. These identify whether the level of workload and compensation required to perform a specified task is satisfactory (Level 1), adequate (Level 2), inadequate (Level 3), or completely uncontrollable. Typically, for aircraft, the Cooper-Harper scale and methodology [Cooper and Harper (1969)] is used for this process. The quantitative data are a combination of parameters describing the vehicle dynamics and task performance that is used to characterise the vehicle and to ensure that the specified manoeuvre was indeed performed. The qualitative and quantitative data sets are correlated to form a handling qualities database upon which criteria are based. Criteria may be partitioned to align with different axes of control and different phases of the mission. For example, in air vehicles there are different criteria for each axis and there may by different criteria for the takeoff and landing phases of the mission as opposed to the up-and-away phase, or weapon delivery phase, of the mission.

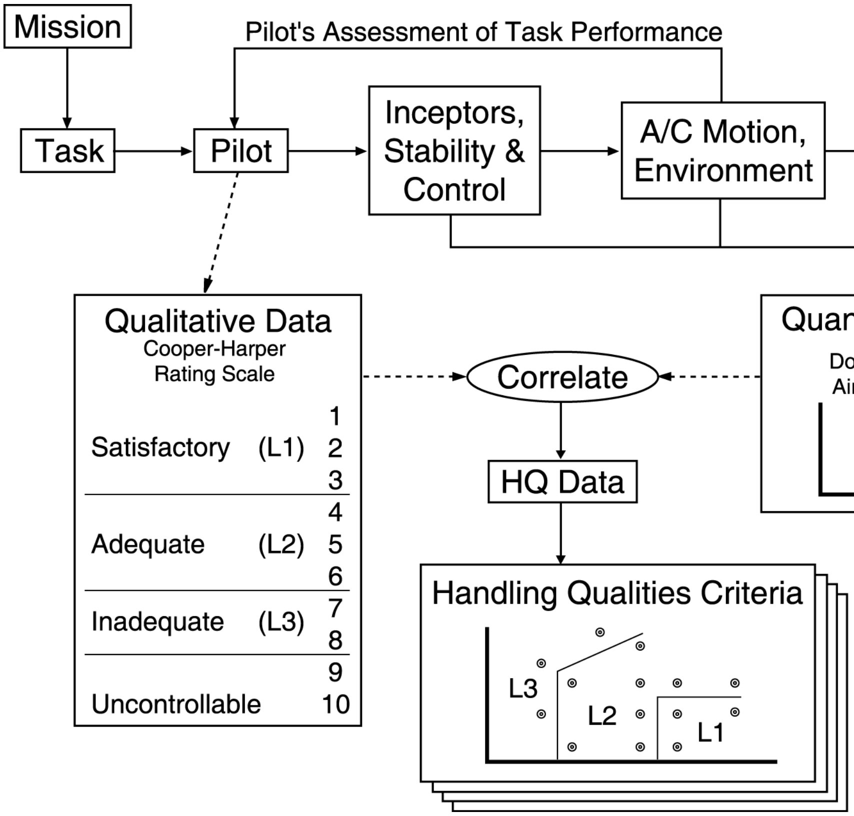

Fig. 5.2 - Schematic for developing handling qualities criteria (air-domain example).

Handling quality design criteria are usually collected into a specification or standard. Some discussion of handling quality specifications or standards for the various domains follows.

5.2.1 Land

In land vehicle development, the behaviour of the vehicles is evaluated by means of special road test-procedures. It should be noted that the dynamics and the handling qualities are not clearly distinguished from each other in these tests. However, we attempt to assign the different tests to those categories, using the definitions:

- Dynamics - the behaviour of the vehicle itself without control systems and without variable inputs by the driver; traditionally referred to as the open-loop response of the vehicle.

- Handling - the efforts of the driver necessary to maintain the course and the speed and to control the vehicle safely.

The test procedures used for vehicle development and for vehicle assessment have been standardised (DIN, ISO); however the standards do not include governmental regulations on fitness for travelling on public roadways. There is one exception, concerning the braking capacity (minimum deceleration), which is subject to rigorous performance verification.

The vertical dynamics of the vehicle, while important from a ride quality point of view, are generally not evaluated in any great detail. The majority of performance and handling interest concentrates on lateral dynamics, such as directional stability (monotonic as well as oscillatory), sensitivity to disturbance, steering characteristics in a curve (understeer or oversteer), and the dynamic vehicle response to unsteady steering inputs (e.g. a step-like or periodic inputs).

The following modes of control are found in the various tests:

- free control (hand free steering wheel)
- fixed control (steering fixed at a constant angle or changed according to a given program)
- ideal driver (steering in such way that the vehicle follows exactly a given course)

And there is the usual distinction made between open loop and closed loop operator control.

The vocabulary of vehicle dynamics has been defined in the DIN 70 000 and is based on the U.S.-American standard SAE J 670 e and the international standard ISO/TC 22/SC 9/WG 1. Standard test-procedures have also been defined; however, not all countries have adopted these definitions. Table 5.1 shows the international standard test procedures for land vehicle control.

Table 5.1 - Test procedures and standards for land vehicle control

Standard	Test	free control	fixed control	ideal driver	open loop	closed loop	vehicle dynamics	vehicle handling
ISO 4138	Steady state circular test procedure			+	+		+	+
ISO 7401	Lateral transient response test procedure with step input		+		+		+	
ISO/TR 8725	Transient open-loop response test procedure with one period of sinusoidal input		+		+		+	
ISO/TR 8726	Lateral transient response test procedure with random input		+		+		+	
ISO 7401	Lateral transient response test procedure with pulse input		+		+		+	
ISO/TR 3888	Test procedure for a severe lane change manoeuvre			+		+		+
ISO 7975	Braking in a turn		+		+		+	

Another very typical lateral dynamics test of land vehicles is the lane change test, defined above, and shown in Figure 5.3 below:

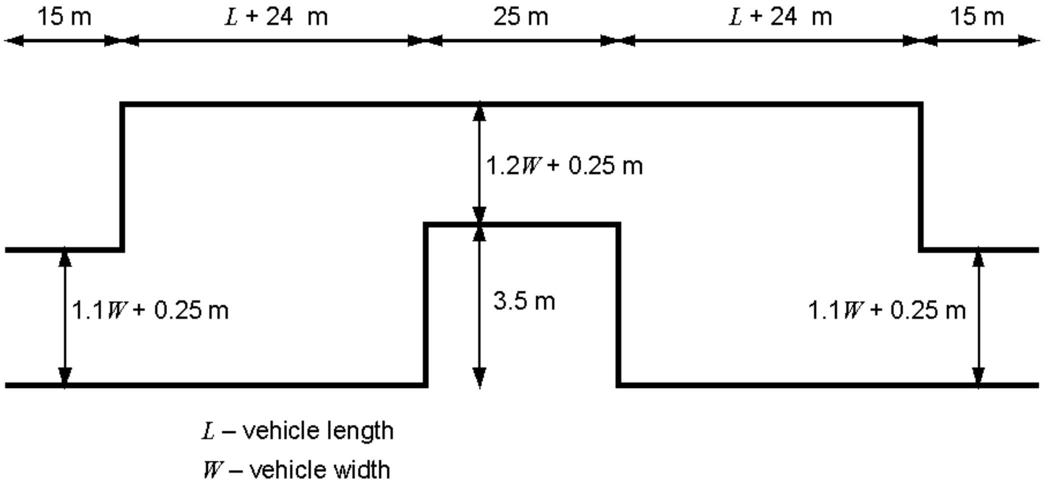

Figure 5.3 - NATO (AVTP 03-160) Lane Change Test Course

5.2.2 Air

In the air domain, there are distinct handling qualities specifications or standards for the different classes of air vehicles, i.e., fixed wing, rotary wing (rotorcraft), vertical take off and landing (VTOL) machines, etc.

The US Department of Defence Joint Services Specification Guide [Mil (2000)] is the official document that contains fixed-wing aircraft handling qualities criteria. Previous variations of the official flying qualities specification documents, published in the 1940's, 50's, and 60's, started as a simple list of manoeuvres that had to be performed to indicate that the aircraft was satisfactory for its mission. As more and more data were acquired, the MIL-F-8785 series of specifications was developed as collections of aircraft control and dynamic response parameters that had been found to give satisfactory handling qualities for the various tasks. These requirements were expressed in terms of linear parameters, and were often misapplied in practice. The latest version again contains demonstration manoeuvres for use in evaluating the system during the design process, in addition to the quantitative requirements to be used for design guidance.

The US Army Aeronautical Design Standard – 33 [ADS (2000)] is the current document applying to the design of rotorcraft. It also contains an extensive combination of dynamic criteria that have been verified to engender specific handling qualities characteristics with a variety of specified manoeuvres that can be used to validate the level of handling qualities (as defined in section 5.2) that a specific vehicle possesses. The development of this standard provides an excellent example of how handling qualities based criteria are created.

In ADS-33, one specific requirement is the bandwidth criterion. This is a frequency-based criterion aimed at short-term control response; it includes the bandwidth parameter (ω_{BW}) and phase delay (τ_p) parameter. Generally, a good system will have a high bandwidth and poor system will have a low bandwidth. Physically, low values of bandwidth indicate a need for pilot lead equalisation to achieve the required mission performance. Excessive demands on pilot lead equalisation have been shown to result in degraded handling qualities. An example of how the bandwidth criterion and level boundaries in ADS-33 were established follows. For the specific task of a lateral side-step manoeuvre, a series of experiments were conducted on existing in-service helicopters and with experimental variable-stability helicopters to develop the data base shown in figure 5.4. As can been seen in the figure, for the conduct of the specific side-step manoeuvre, there is a clear relationship between the control system parameters (ω_{BW}, τ_p) and the handling qualities ratings gathered from the evaluation pilots. The final handling qualities criteria were developed by establishing curves on the same plot which delineate the various handling quality levels. Ratings of 3 or less are summarized as “satisfactory without improvement” and constitute Level 1. Similarly, ratings of 4-6 are “deficiencies warrant improvement” and are Level 2. Finally, ratings of 7-9 are “deficiencies require improvement” and are grouped as Level 3. As a result of this process, the designer can predict the resulting handling qualities of a design, based on its dynamic characteristics.

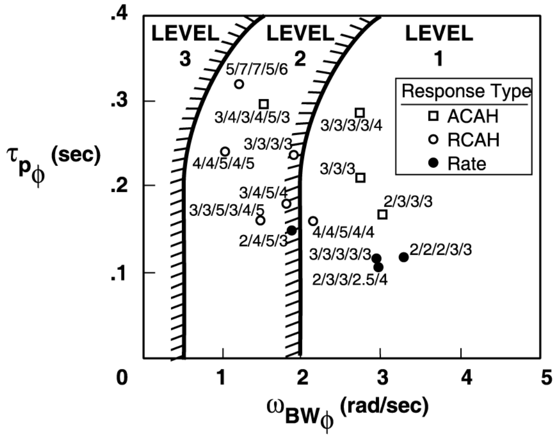

Fig. 5.4 - Handling Qualities Ratings (HQRs) for a sidestep manoeuvre with different control responses.

MIL-F-83300 [Mil (1970)] and AGARD Report 577 [AGARD (1970), (1973)] both contain requirements for the handling qualities of VTOL aircraft. They are both written in terms of quantitative criteria. Unfortunately, neither of these specifications has been revised recently and they must be considered obsolete in many aspects.

The Society of Automotive Engineers (SAE) also publishes recommended practices, frequently edited from the military specifications.

5.2.3 Sea

For commercial shipping, there are standards, guidelines, and legislation, at both national and international levels, regarding ship manoeuvring and operation. These may be the default for naval ships in the absence of relevant naval criteria, although, as noted below, there is a movement towards convergence of rules and standards. Standards addressing the ship response in a controls-fixed (or in some way predetermined) manoeuvre are included in the IMO Interim Standards for Ship Manoeuvrability [IMO (1993)]. Operator-in-the-loop issues are less easily amenable to quantification, and are more likely to be specified in terms of local navigational — e.g., harbour or channel — regulations.

Lowry (1990) examined, in the context of commercial shipping, how the responsibility for preventing CRGs (collisions, ramming, and groundings) should be apportioned between owners, designers, legislation/standards, etc. He quotes USCG statistics that one third of CRGs could be attributed to poor ship controllability, one third were unavoidable, and one third were the result of human error, and furthermore asserts that some vessels that are apparently uncontrollable in one mariner's hands are quite controllable in another's. Figure 5.5 illustrates the complex interaction of standards, legislation, etc., in the world of commercial shipping. The IMO sets standards for manoeuvrability [IMO (1993)] and related issues [IMO (1987)], as do classification societies [Lloyds Register (1999)] and national bodies. SOLAS [IMO (1974)] governs overall safety of operation. Determination of the "legislative envelope" is presently somewhat different in the naval context, and mission and requirements become additional inputs to the design and assessment loop.

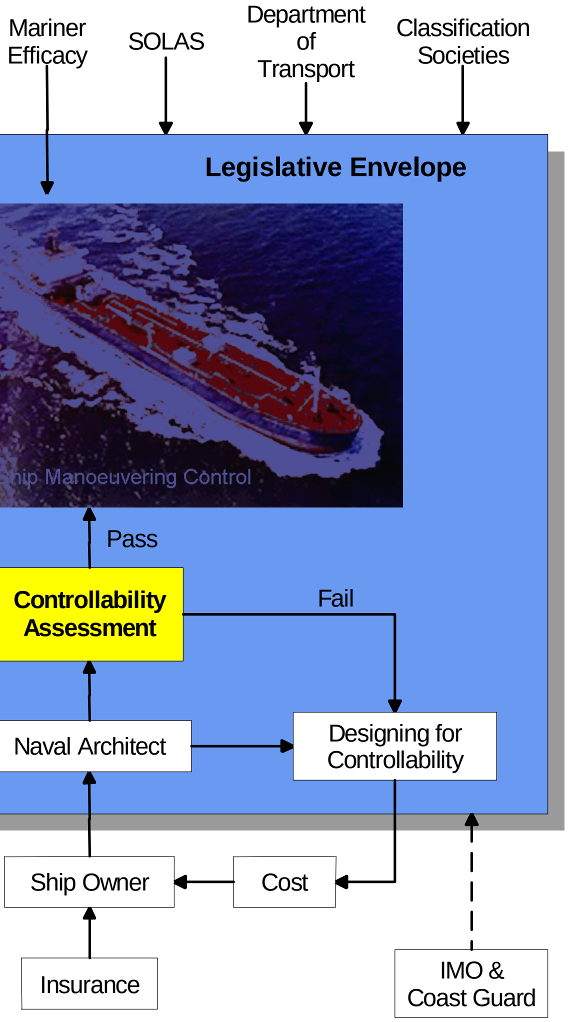

Fig. 5.5 - Ship Manoeuvring Control: Where does the Onus Lie?
(Adapted from Lowry (1990).)

It is worth noting that a number of the classification societies are currently developing naval ship rules. The Royal Institution of Naval Architects Warship 2002 Symposium "Safety Regulation and Naval Class" will address this development.

Response of the controls and effectors is rarely an issue since their time scales are generally at least an order of magnitude less than those of the ship in a manoeuvre. The same observation applies to operator response.

A NATO standardisation working group, ST–NSM, Specialist Team on Naval Ship Manoeuvrability (under the NATO Naval Armaments Group), is currently investigating the development of specific warship manoeuvring criteria.

Unlike conventional aircraft, large ships are likely to be made a little directionally unstable in order to be manoeuvrable in harbours and other confined waters. This practice imposes an additional need for training in ship handling. Submarines are often designed to be directionally unstable in the horizontal plane, but most are directionally stable in the vertical plane. Under manual control, unconventional sternplane configurations and control reversal at low speed are potential handling issues.

Handling qualities in a submarine context are complicated by the typical high degree of automation in system control, which, in addition to handling the primary system functions, may include signature management. Platform control (propulsion, diving, and manoeuvring) system consoles are now generally linked for monitoring and limited control capability so that, for example, unmanned engine room and auxiliary machinery spaces have become standard. Combat systems (sensors, navigation, and weapons) are very highly integrated, with distributed data processing and multiple redundancy.

Figures 5.6 and 5.7 illustrate modern submarine manoeuvring consoles; the first, although highly automated, retains helmsman/planesman/supervisor redundancy for manual control; the second is an example of a one-man manoeuvring station used in current submarine designs.

Fig. 5.6 - USS Seawolf manoeuvring station

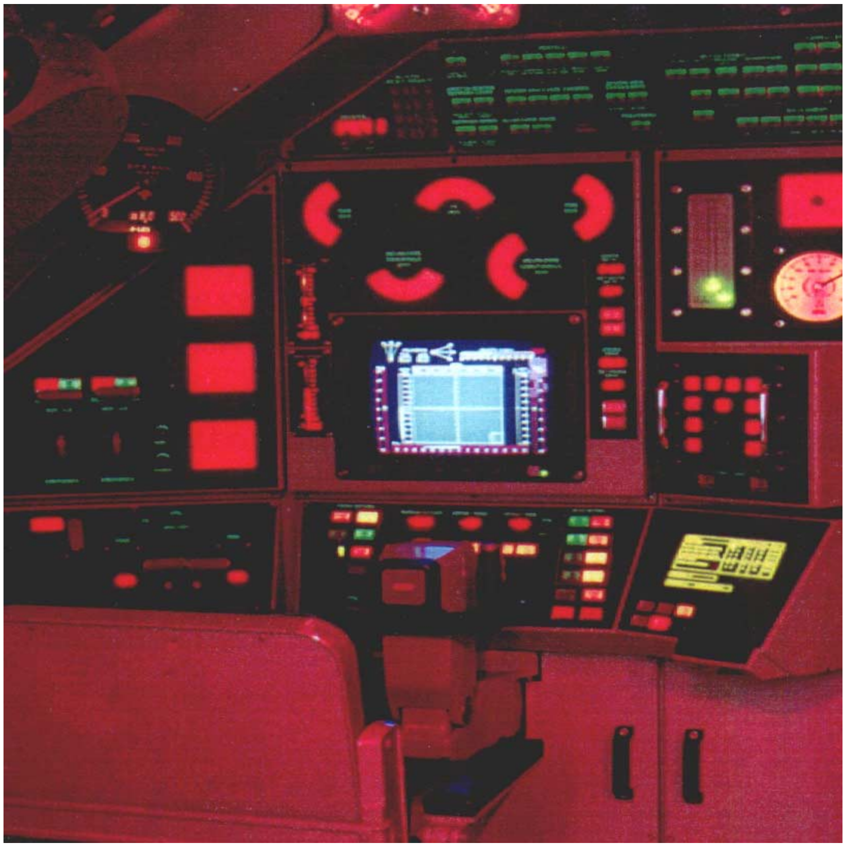

Fig. 5.7 - SEPA submarine steering station mock-up.

The trends noted above for submarines apply in general to surface warships also. However, there are differences: training requirements for the surface ship are a little less rigorous, and subsystem automation, and total system integration, is more pervasive, especially in modern small craft. New large ship designs use Integrated Bridge Systems(IBS), figure 5.8. The IMO states: “An integrated bridge system is defined as a combination of systems which are interconnected in order to allow centralised access to sensor information or command/control from workstations, with the aim of increasing safe and efficient ship's management by suitably qualified personnel”. Performance standards for integrated bridge systems were adopted by IMO in 1996 (Resolution MSC.64(67)).

Fig. 5.8 - Typical Integrated Bridge System arrangement (Kongsberg Maritime Ship Systems (KMSS) Bridgeline series).

A typical IBS will incorporate manoeuvring controls, conning display, primary machinery controls, colour radar, electronic chart display, and night vision. Expert systems are provided to aid the operating team.

Even higher degrees of system integration, such as incorporating the IBS, damage control, full machinery and auxiliary control, communications, and a number of other systems, are being explored by the US Navy in the Smartship program (http://www.dt.navy.mil/smartship), for which USS Yorktown (CG-48) was the prototype. The aims of this program include reduced crewing and crew workload, higher reliability, reduced vulnerability, and Commercial-Off-The-Shelf (COTS) implementation.

Additional specifications to define desirable ship design characteristics are included in STANAG 4154 and STANAG 4194 [NATO (1995), (1995)b, (1997)]. In general, however, these specifications deal more with the overall vehicle performance level desired, than with a consideration of vehicle handling qualities. Closer to the issue of handling qualities are a number of documents that concern the relationships between the human operator and the naval vessel [Colwell (2000), Holcombe *et al.* (1995), Crossland *et al.* (1994), Colwell (1994), Colwell and Heslegrave (1993), Graham and Colwell (1990), and Colwell (1989)] that concern the. While these documents are clearly involved in the discussions of handling qualities, they illustrate the fundamental difference between maritime and air communities in consideration of vehicle handling qualities in its own right.

5.3 VEHICLE OPERATORS AND HUMAN FACTORS

A clear similarity between land, air and sea domain vehicles is the direct involvement of the human operator in the control of a vehicle during its mission. While the environment in which the operator exists is varied, largely due to the ability of vehicle to accelerate in each axis and its tendency to transmit external disturbances to the operator, the same principles apply in all cases.

The ergonomics of the operator station, including the information displayed, and the physical characteristics of the vehicle in manoeuvres, like its time scale, will impact the operator's ability to analyse a situation and to react to changing events. For example, human response time has a relatively low impact on the performance of a submarine in a manoeuvre, unlike an aircraft. Also, as response times of a submarine and a combat aircraft to disturbances are quite different, approaches and techniques for analysing the situation and taking action by the operator may be quite different and will need to be adapted to the particular time scale of the vehicle.

Without question, basic anthropometric data are a basis for operator station design, be it a tank driver station, a fighter cockpit, or a submarine helmsman station. Consideration of information presentation, the other end of the human factors spectrum, is also common to all vehicle operators. The capabilities of an operator to guide the vehicle and to react to stimuli are also highly variable, depending on the visual, oral, vestibular, and tactile information presented and are influenced especially by environmental factors such as:

- visual conditions
- oscillations, and vibrations
- accelerations
- noise
- climatic conditions (humidity, and temperature)
- communication
- lack, or overload, of information

Finally it should be considered, that the level and duration of environmental impacts as well as psychological stress, especially in combat situations, play a major role in reducing the operator's capabilities. By means of new technologies it is possible to assist the operator and to reduce the impact of environmental factors.

In figures already presented in this report in Chapter 4, the similarity between modern tank driver stations and aircraft cockpits is clear. This similarity is becoming equally obvious in certain naval vehicles. Studies of crew compliments, task distribution and resource management are central to all new design efforts of military vehicles.

Operator training and ability may be factored, indirectly or directly, into platform and control system design and standards. The IMO [IMO (1972) and IMO (1978)] and national bodies set training standards for commercial shipping. Standards are more rigorous in the naval context. Intense and continuous training is required of submarine crews, perhaps less for naval surface ships, for all scenarios including degraded controllability down to the most basic manual control. MLDs (see Chapter 2 operating envelopes) reflect a rigorous training requirement in the time allowed (typically seconds) to identify and correctly respond to an emergency situation; the penalties for a delayed or incorrect response can be catastrophic. However, outright negligence and sudden operator incapacity are issues that training and regulations [Lowry (1990)] cannot ultimately compensate for. It may be difficult and costly to provide automatic systems to override the operator, but it is done, perhaps more often in the civilian than military environment, and it is often enforced by legislation.

The degree of the vehicle control station automation and integration has a direct impact upon the handling qualities. Automation in any form, when done correctly, relieves operator workload. Poorly done, however, it can be of little benefit or even cause increases in operator workload and a reduction in situational awareness.

To further this discussion, one can consider the remotely controlled vehicle, in either land, air or sea domain. In these vehicles a central theme of how the operator can have sufficient situational awareness to perform the control task is obvious. Issues such as tele-presence, the use of immersive and conformal displays, and the level of automation required to optimise man-vehicle performance are central to further improvements in the operational effectiveness and utility of these vehicles.

5.4 CURRENT ISSUES AND TECHNICAL CHALLENGES

5.4.1 Validated Data Bases for Criteria

As the various versions of air vehicle handling qualities specifications evolved to providing design criteria, they were usually substantiated by a database. This has generally been gathered by means of ground-based and in-flight simulation of both good and bad response characteristics. These data bases evolved as flight envelopes expanded to domains of high angle of attack and high angular rate. Some comparisons of actual aircraft characteristics with specification criteria have been published [Morgan and Baillie (1993), Strachen *et al* (1994), Ockier (1998), Blanken *et al* (2000)]. Analogous data bases for land and sea vehicles have generally not been published in the open literature. Changes in national laws and public perceptions, developments in procurement and support, and recent accidents have increasingly led to navies re-assessing their safety management policies. Several classification societies have developed or are developing naval ship rules. Similar programs would benefit the land vehicle design communities.

5.4.2 Information Overload and Fusion

Modern vehicles are becoming very complex multi-sensor systems, as information from many different sources is becoming readily available. Information fusion seeks to alleviate the additional workload that this creates for the operator by combining data in order to avoid information overload. Currently, for example, integration of advanced navigation and low-level guidance information using INS, GPS, and a terrain database is an important challenge for the operation of aircraft. Information fusion can lead not only to improved mission quality, but also to improved situational awareness. In this context, new requirements on cockpit (or other operator station) and display design have to be considered.

In the main battle tank, for instance, the internal and external information often exceed the capacity of the crew. Studies have shown, that this load can be reduced to a much lower level (less than 50%), with a guidance system that presents information visually on a screen instead of using oral information via headphones. Such systems can increase combat effectiveness and can allow the reduction of the number of crewmembers e.g. from four to three, or even two.

To achieve this goal, new automatic systems will be developed, including algorithms allowing a certain level of autonomy in which decisions are taken by the control system. Compromises between the levels of authority that are delegated to the control system, and to the operator, are elements of the solution to the workload problem.

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Chapter 6 – Conclusions and Recommendations

Over the course of the preceding five chapters this report examines the dynamics, system identification, control and handling qualities issues associated with land, air, sea and, in a very limited way, space vehicles. The discussion at times demonstrates the significant differences between these vehicles, owing to their operational environments, military role or even, just plain physics! On the other hand, at times the discussion concerns areas where the word "tank" could be easily replaced by "truck", "aircraft", "helicopter", "ship" or "submarine", and yet the meaning, implications and value of the statements would be equally valid.

In this final chapter, the SCI-53 technical team presents a list of commonalities, differences, and significant technical issues that have been highlighted by the material presented in the previous chapters and by the discussions of the team members. This list is not prioritized or ordered in any fashion. It is hoped that this ad-hoc discussion will generate ideas leading to collaborations between experts in the various vehicle domains.

6.1 COMMONALITIES AND DIFFERENCES

6.1.1 Terminology

One of the most obvious issues that became clear over the development of this report was the differences in vocabulary in use in each operational environment and how discussion of a given concept, such as vehicle handling qualities, was initially hampered by a lack of commonly held fundamental definitions. As a prime example, it was only through the adoption of the phrase "ease of use" for the principle of handling qualities, that the discussion took a meaningful form between SCI-53 members on this topic. It is quite apparent that this type of barrier to communication and collaboration, driven by domain or even vehicle-specific jargon, needs to be overcome to allow a meaningful transfer of knowledge between experts. While a standardized vocabulary is well beyond the scope of this document, and perhaps would be a futile effort anyway, given the rapidity of technological change, it is apparent that all experts must make conscious efforts to define, and clarify concepts at a fundamental level in order to alleviate this potential obstacle to communication.

6.1.2 Vehicle Designer Objectives

At first glance the fact that vehicle designers often share the same basic design objectives goes without saying; however, upon reflection, this commonality requires further definition. While vehicle design is rooted in mission requirements and task definitions, the underlying design tradeoffs, considering, for example cost-effectiveness or reliability are quite similar for all vehicles. Modelling techniques employed to assess design tradeoffs, while surely different for tanks, aircraft, ships, and submarines, certainly share fundamental principles that could be a valuable area for collaboration.

6.1.3 Time Scales

As clearly illustrated in Figure 2.3, the time scales of land, air and sea vehicles are significantly different. The characteristic time scale, length of vehicle / forward speed, differs from .01 seconds for missiles, through to 10s of seconds for large ships. This characteristic defines in certain senses, the overall vehicle dynamics, and certainly the control system requirements. On the other hand, given that the human operator time constant is essentially invariable, there is both a fundamental difference and a commonality in the discussion of time scales.

6.1.4 Vehicle Transient Response

Related to the issue of time scales is the importance of the transient response of the vehicle to either control input or external disturbance. In the case of aircraft, the transient response may occur at the same time scale as the pilot control, thus the transient is of paramount importance in the control system design. In the case of a large ship, however, there is a large frequency separation between the helmsman control input and the transient response of the ship to that control input. In this case, the transient response is much more of a ride-quality issue than a control issue.

6.1.5 Formal Emphasis on Handling Qualities

As illustrated in Chapter 5, there is a significant level of difference in how consideration of the handling qualities, or ease-of-use, of a vehicle is a part of the design process. While the aircraft and helicopter field has developed extensive vehicle dynamics criteria to provide satisfactory handling qualities, land and sea vehicle design seems to be more firmly rooted in the practices of rules-of-thumb and conventional wisdom. Closed loop performance of specified tasks is a common means of measuring the suitability of a vehicle for a given role, be it a tank, aircraft or ship, but upon failing to achieve the desired performance, the aircraft designer will focus on improving the vehicle dynamics, while the tank or ship designer is initially more likely to focus on improving the training of the operator. This difference may be diminishing with the increased use of manoeuvring simulations to evaluate closed loop performance in all environments, since it is now much easier (and cheaper) to identify and alleviate a problem with the dynamics early in the design process. However, formal emphasis on evaluating handling qualities remains largely confined to the air community.

6.1.6 Operator Skill and Training Level

The discussion of handling qualities above leads directly to consideration of operator skill and training, and once again there is both similarity and difference between domains. In all domains, the skill of the operator can clearly compensate for undesirable vehicle characteristics and can lead to improved performance for a given set of circumstances. In the land domain, and especially in the case of truck operators, the initial operator skill level is relatively low. In such a case one can choose between two strategies:

a) design the vehicle so it is highly automated or simple to operate, i.e. skill level is not a factor in accomplishing the mission,

or,

b) when deficiencies in task performance arise, invest in operator training to develop the necessary compensatory strategies to counteract the vehicle deficiencies.

Given that the average operator has a low level of initial skill, either of the two strategies may work and therefore the vehicle designer must consider the tradeoff of vehicle cost versus training cost required for any given feature or deficiency of the vehicle.

On the other hand, the aircraft operator is, in general, highly skilled, being the subject of extensive training prior to assignment on a given aircraft type. In this case, while a little more training may not be cost prohibitive, it is less likely to successfully compensate for a given vehicle shortcoming since the operator is already trained to a high level of competency. In the aircraft case, modifications to the vehicle therefore usually receive more emphasis than increases in operator (pilot) training when task performance deficiencies become apparent.

6.1.7 Single Operator Versus Command Structured Operation

As documented in the preceding chapters, marine vehicles, and to a lesser extent land vehicles, are often controlled by a structured team of many individuals. This approach places additional emphasis on the communication between crew members and creates technical issues regarding how the communication is performed. In contrast, one or two pilots in an aircraft perform their tasks fairly independently, interacting with battle controllers and other asset commanders at a less frequent level. The above being said, with pressures to create an integrated, effective battle force that is seamlessly connected between battle commander and vehicle operator, the distinction between the level of independence of a pilot versus that of a submarine helmsmen is slowly becoming less obvious. In all cases, considerations of individual multi-tasking and workload are hugely important, as are the issues generally wrapped up in the phrase “situational awareness”.

6.1.8 The Use of Augmentation

The level of augmentation present in the various vehicle classes is different, depending upon the circumstances. Warships are predominately unaugmented (and the classic ship/submarine configuration is underactuated); however augmentation is being applied more and more, especially in the context of thruster use. Land vehicles use, in numerous cases, active components such as braking, traction or inflation systems, but are also predominantly unaugmented. In contrast, most military aircraft are highly augmented, from the use of rather conventional stability augmentation systems in older aircraft, through to the more and more common use of fly-by-wire which allows a marked decoupling between the dynamics developed by the aerodynamic configuration of the vehicle and those available through the active use of control surfaces.

6.1.9 Physics

It should be obvious to almost every reader of this report that vehicles in all four environments are subject to the same overriding physical principles. This straightforward observation highlights the fact that there are a huge number of technical design problems, particularly in the dynamics area, that are identical for land, air, sea, and space vehicles. A very simple example of this is the dynamic problem of liquid sloshing in a tank within a vehicle. While the relative magnitude of the forces produced may be different in each type of vehicle, the basic problem remains the same and the same analysis techniques are applicable. In a similar vein, current efforts to understand, model, analyse, and improve non-linear behaviours seem to be common to all vehicle domains at the present time. Once again, the ability to simplify, or simply ignore the non-linear elements of a problem is driven by the particular circumstances; however the fundamental commonality still exists.

6.1.10 Standards and Specifications

For all vehicle types, a wide range of standards, specifications and rules of thumb exist which govern the design and evaluation of a vehicle. Although some fundamentals apply generally, these rules reflect the exigencies of their respective environments, and it was not evident to the SCI-53 team that much is transferable between them. Each specification has its strengths and weaknesses, and the effort to clarify or improve these design guidelines continues for all vehicle classes.

6.1.11 The Use of Simulation in Design and Evaluation

It is clear that there is a wide spread increase in reliance on simulation and modelling to analyse, understand, and characterise vehicles and their roles in the battlespace. With such a trend, the level of modelling fidelity and the ability to tailor model fidelity according to the purpose of the simulation are current issues in all vehicle domains.

6.1.12 Fluid Mechanics

Clearly both air and sea vehicles are fundamentally driven by the application of fluid dynamic principles.

6.1.13 Operational Envelopes

From the discussions of chapter 2, it is apparent that all vehicles currently have regions of operation that are to be avoided for one reason or another. These operational envelopes are characterised differently for tanks, trucks, aircraft, helicopters, ships and submarines due, in part, to the vehicle-specific characteristics that drive the envelope, but also due to common practices. In all cases, however, the intent is the same, to provide the operator with a quantity that describes the limit in question, with an active indication of how close the vehicle is to the limit, and the means for the operator to guide the vehicle so it can avoid operation in the forbidden areas. In all vehicle classes, these requirements are leading to the concept of carefree control, which is being developed to reduce operator workload and to improve the operator’s ability to exploit maximum vehicle performance.

6.1.14 Vehicle Production

The number of vehicles produced of a given design defines the approach that the design and production team may take. For example, although ships usually have a very short production run (military ships are rarely one-of), it has been standard practice to make changes, which may or may not be retro-implemented in the already-built vessels, during production. Invariably, no two of a class are exactly the same, even nominally. Today’s contract-acquisition policies, in which the client (i.e. the navy) pays a heavy penalty for making changes, and the cost and complexities of logistical support for a mixed class, now tend to discourage this practice. On the other hand, aircraft and land vehicle prototypes seldom enter military service, while the production run of the finalized design may run into the hundreds or even thousands. This difference has significant impact on the application of design criteria, the inertia for change, and the ability to improvise during construction.

6.1.15 The Effect of Environmental Disturbances

Each class of vehicle operates in its own environment with inherent extremes in conditions. As illustrated in Chapter 2, the differences in environmental concerns are quite marked for each vehicle type. As an example, a tank must be designed to traverse physical barriers of specified extent, and must be concerned with the effects that the preceeding tank has had on the path or road that it is following. An aircraft is generally designed to operate over the range of atmospheric disturbances, although those are easily amplified if one considers aircraft carrier operations or ship-borne helicopter operations where the wake of ship superstructures, coupled with sea spray, are the extremes. The weather plays an even more dominant role for ships due to the speed of weather patterns, which may at times exceed that of the vehicle. Conversely, a ship may have no choice other than to traverse bad weather when responding to an operational requirement. Ultimately, however, most ships must be capable of at least surviving the worst conceivable weather encountered in open ocean, even though no other operation is possible.

6.1.16 Weapon Systems

In almost all vehicle classes, the weapon systems integrated into the vehicle prescribe additional operational constraints. Launch or firing envelopes often demand higher levels of stability than are otherwise required. Smart weapons with weapon designator systems alleviate some of these requirements, but at a highly elevated cost.

6.2 COMMON TECHNICAL CHALLENGES

One of the objectives of the SCI-53 team, and of this report, was to identify potential areas of technical work that could be enhanced by the collaboration and coordination of experts in the land, air, sea, and space domains. This section presents descriptions of some technical problems that could serve as initial projects for such activity.

6.2.1 Dynamics Problems

From the material presented in Chapter 2, the following topics (or the physics underlying them) are deemed to have sufficient commonality to be appropriate for the concentration of cross-environment teams focused on their resolution or improvement:

- Accurate modelling of towed system dynamics
- Accurate modelling of fluid slosh dynamics
- Non-linear modelling techniques in general
- Consideration of limits, such as on actuator travel, and how they effect dynamics
- Modelling of soil-tire/track interactions
- Ship dynamics and controllability in following seas
- Solving the unique problems of unmanned vehicles i.e. those potentially generated by scale, autonomy, and very high rate and acceleration envelopes

6.2.2 Modelling and System Identification

As stated many times here, the use of modelling and simulation is central to the design and evaluation of vehicles. Current economic pressures are further encouraging the use of these tools to understand physical problems before they arise during test programs, and to better evaluate how design choices affect the final vehicle operational effectiveness. Some areas where coordinated cross-environment teams could be employed include:

- Improving the ability to scale vehicle models for test purposes
  - Ship propulsion systems (cavitation/Froude/Reynolds number scaling)
  - Aircraft high angle of attack characteristics
- Control oriented system identification – the modelling of uncertainties to assist the accurate development of control systems
- Developing rapid modelling techniques

- Better understanding of the balance between hardware in the loop and synthetic environments for optimal design analysis
- The coupling of analysis tools in full models (i.e. CFD + structural dynamics + controls +…) to represent all facets of the complete integrated vehicle-weapon system
- Modelling of failure scenarios
- Modelling of coupled, autonomous sensor (sonar) systems in terms of dynamics and sensor performance

6.2.3 Vehicle Control

Certainly the techniques used to develop control systems are, by their very nature, applicable to all vehicle domains and thus form a very broad area of potential collaboration. Particular collaborations could also be performed in the following areas:

- Use of multi-axis or multiple control effectors for more optimal control of ships
- Robust and fault tolerant control systems
- Automated convoy operations (land, air and sea)
- Control of vehicle attitudes and manoeuvres to minimize signatures w.r.t. known threats (air, sea)

6.2.4 Vehicle Performance and Handling Qualities

As identified in Chapter 5, ease of use and performance concepts are the final measure of the operational effectiveness of a military vehicle. Several areas where initial collaboration between domains could be fruitful include:

- Developing land and sea experience and rules of thumb into more formalized design criteria focused on ease of use
- Tailoring vehicle characteristics to reduce the required operator skill level, either to reduce the overall operator training requirements, or to allow for a greater concentration on tactical decisions
- Improving the agility of the vehicle (e.g. hummingbird agility)
- Improving awareness of, and capability to respond to, operational or physical limits (i.e. carefree handling, collision avoidance)
- Improving situational awareness

6.3 THE WAY AHEAD

This report is the product of a solidly “cross-environment” team of experts representing the following communities:

- Tanks
- Automobiles
- Other Land Vehicles
- Fighter Aircraft
- Helicopters
- Ships
- Submarines

It provides a relatively high-level overview of technological issues for land, air, sea and, to a very limited extent, space vehicles. During the development of the report, it was realized that there were clear opportunities for meaningful collaboration between vehicle experts although the means to stimulate and initiate these collaborations were not readily apparent. The members of SCI-53 decided to address this problem by proposing an RTO-SCI Symposium focussed on the technical material highlighted in this report. It is expected that this symposium will bring together a critical mass of experts in an environment where they can discuss their unique challenges and, in so doing, real, focused, and meaningful technical collaborations will be initiated. The symposium, “Challenges in Dynamics, System Identification, Control and Handling Qualities for Land, Air, Sea and Space Vehicles”, will be held on May 13-15, 2002 in Berlin Germany.

It is hoped that this SCI-53 report, the symposium, the publication of the symposium proceedings and a technical evaluation report, will serve to establish momentum in the areas of dynamics, system identification, control and handling qualities, particularly emphasizing how each operational community can learn from the others.

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Appendix I

Research Facility Descriptions

Description of the Air Vehicle Simulation Facility at the Air Vehicles Directorate Air Force Research Laboratory

1. Name of the Facility and Location

Air Vehicle Simulation Facility
AFRL/VACD
2180 8th St, Ste 1
WPAFB, OH 45433-7505 USA
http://www.va.afrl.af.mil/vac/vacd/techinfo.html .
Contact: Gary Hellman

2. General Facility Description

The Air Vehicle Simulation Facility applies engineering flight simulation tools to support air vehicle and weapon system technology integration, assessment, demonstration, and transition under realistic mission conditions, on both local and long haul networks. It uses simulation to synthesize advanced technologies encompassing the air vehicle, crew station, flight controls, propulsion system, avionics, and weapons within their environment. It assesses mission and combat effectiveness, survivability, flying qualities, flight safety, and workload impact of these technologies.

There are four simulation platforms maintained by the facility:

- Mission Simulator One (40’ dome)
- Large Amplitude Multi-mode Aerospace Simulator (LAMARS) (5-DOF motion simulator)
- Mini-Crew Stations (MCS)
- Infinity Cube

All four of these platforms can be run independently or in conjunction with one another to provide a simulation capable of single ship or multi-ship technology evaluations.

3. Main Technical Data

- Visual System
  - Hardware: Evans & Sutherland, SG, PC based systems
  - Projection System: depends on simulator (ranges from single channel OTW display in the MCSs to four channel [front, left, right, top] Out-The-Window display in the Infinity Cube)
  - Visual Databases: several visual databases including Multi-Spectral Database of Generic Composite Scenario (GCS) and Western Open Air Range (WOAR)
- Computer Equipment
  - SG machines (O2s to Onyx2s)
  - PCs
- Cockpit Description
  - Generic research fighter-type cockpits (touch screen monitors, rudders pedals, sticks, throttles)
- Software

– Engineering Models: F-16, F15A,B,C,D, VISTA/NF-16D, Future Requirements Evaluation Demonstrator (FRED), others

- Engagement Level Models: Man-In-the-Loop – Air-to-Air System Performance Evaluation Model (MIL-AASPEM), Enhanced Surface-to-Air Missile System (ESAMS)
- Mission Level Models: Joint Interim Mission Model, Digital Integrated Air Defense System, Extended Air Defense Simulation (EADSIM)
- Campaign Level Models: Intelligence, Surveillance, Reconnaissance Simulation (ISRSIM)
- Stealth Viewers: Virtual Battlespace Management System (VBMS)
- Mission Planning/Rehearsal: Air Force Mission System Software (AFMSS), SubrScene

4. **Simulation Activities**

Several different types of simulations are conducted in the facility. The first, Flying Qualities Simulations, are typically used for testing and evaluating control system designs and their effects on aircraft handling qualities. The Pilot Induced Oscillation Simulation Study and the Innovative Control Effectors Simulation Study are recent handling qualities simulations.

The second type of simulation, Air Combat Simulations, are typically used for testing and evaluating one or more weapon systems in a realistic threat environment using both piloted and digital players. Examples of such simulations conducted at this facility include the VISTA Advanced Capabilities Simulation Study, and the requirements definition study conducted in support of the Joint Strike Fighter development program.

The third type of simulation, Network Simulations, consist of two or more remote simulation sites communicating together to provide one cohesive simulation environment. Communication between the remote sites is done using the Distributed Interactive Simulation (DIS) protocol or the Higher Level Architecture (HLA) protocol. The Transatlantic Research into Air Combat Engagements Simulation Study and participation in the recently completed Joint Expeditionary Force Experiment 2000 (JEFX2000) are examples of Network Simulations.

The fourth and final type of simulation conducted in the facility is referred to as Simulation Based Research and Development (SBR&D). SBR&D is the integrated use of modeling and simulation across AFRL programs, with the goal of reducing research and development cycle time and cost. The goals of SBR&D are: 1) speed the identification of promising technologies and concepts out of the AFRL Technology Directorates and 2) develop an affordable, flexible, and mission-oriented means to thoroughly assess AFRL technologies and their worth to the warfighter community before committing a large amount of R&D resources. The first simulation study being conducted in the facility is the concept of a new unmanned Intelligence, Surveillance, and Reconnaissance vehicle.

5. **Outstanding Points of the System and Limitations**

- LAMARS – only 1 of 2 large motion simulators in the US
- Infinity Cube – a state-of-the-art collimated out-the-window display system that provides a wide field of view to the pilot – currently limited to 4 channel system
- Networked connections to modeling and simulation facilities throughout DoD and its contractors, including the Defense Research Engineering Network
- High fidelity simulation capability from the basic engineering level through both air-to-air and air-to-ground mission level

6. **Future Developments**

- Increase in the number of Infinity Cubes (also to 6 channel visual system) and high-end fidelity cockpits
- Movement to all PC based simulations
- Growth of Simulation Based Research and Development across all of the Air Force Research Laboratory Technology Directorates

CMS

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Contact: Anthony Patterson, Director

1. Overview

The Centre for Marine Simulation (CMS) provides a broad range of simulation-based training and applied research services in ship navigation, marine engineering, and ship communications. The training and education component contribute significantly to the efficiency and safety of marine operations, and to environmental protection. Training of marine operators with the use of high-fidelity simulators is recognized as effective and cost-efficient. In addition to their direct impact on marine operations, the simulators aid in the design of vessels, ports, and waterways.

2. Facilities

CMS comprises six marine simulation facilities that cover a range of training, educational, and R&D capabilities. They comprise:

2.1 Full Mission Ship Bridge Simulator

This is a 15 tonne, 5×7 metre, fully instrumented ship bridge mounted on a 6 DOF aircraft motion platform. The instrumentation and layout are customizable. Fully loaded, the motion platform provides ±15 degrees in roll pitch and yaw, ±2.13 m in surge, ±2.35 m in sway, and

±0.5 m in heave. Special effects include a variety of buffets and vibrations in all axes of the order of 0.025 g at a frequency of 30 Hz. There is a 360 degree field of view visual scene, and four-channel sound system. Visuals include terrain, typically harbours and confined waters, independently controlled other-ships, and a variety of navigational aids. Own-ships in the simulation database include military vessels, and commercial ships up to 220,000 t.

2.2 Navigation and Blind Pilotage Simulator

This facility consists of an instructor's station and four static fully equipped ship bridges; it is for training navigation by instruments in restricted visibility. The bridges are fitted with main engine controls and indicators, course and rudder controls, autopilot, radar, compasses, depth sounder, loran, decca, GPS, etc. The primary function of this facility is operator certification.

2.3 Dynamic Positioning Simulator

This is a recently implemented static training facility comprising two dynamic positioning control systems with environmental input and own-ship response. Own-ship models presently include a cable-layer, ROV support vessel, and semisubmersible drill rig.

2.4 Ballast Control and Cargo Operations Simulator

This provides ballast and cargo control stations typical of an offshore drilling rig, VLCC, liquid product carrier, or float on float off vessel. The control room is mounted on a motion platform (2 DOF, pitch and roll). The physical effect of motion while controlling trim and stability is considered essential if training objectives are to be met. Simulation scenarios range from routine cargo loading/unloading to damage control situations.

2.5 Propulsion Plant Simulator

The propulsion plant simulator is based on typical engine/control room equipment, and models a single Sulzer or twin MAK diesel plant. It is used for operator certification, training in faulty and deteriorated conditions, and for fuel management.

2.6 Global Maritime Distress and Safety System (GMDSS) Simulator

This facility provides a mixture of actual shipboard communication equipment and computer simulation linked with a live radio station for communications operator training.

Defence and Civil Institute of Environmental Medicine

DEFENCE R&D DÉFENSE

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http://www.dciem.dnd.ca

Contact: Dr. B.H. Sabiston, Manager, Business Development (tel: 416 635 2032)

MARS Virtual Reality Simulator

A low-cost, portable simulator for teaching junior MARS (Maritime Surface/Subsurface) officers the conning skills required of an Officer of the Watch (OOW).

A low-cost, head-mounted display is used to provide a visual environment, while voice recognition and production simulate verbal interactions with a surrogate bridge team. The voice recognition system captures the OOW's spoken orders and encodes them into a format that the simulator can use to adjust helm or engine speed. The system is also used to record verbal responses of the bridge team, simulating unique voices for the yeoman, range man, and helmsman. The voice recognition system is also used to record commands for observation by the Officer Conducting the training Session (OCS). The benefit of this system is that it eliminates the need for instructional personnel to perform the bridge functions, eliminates a source of uncertainty in the assessment of the trainee's performance, and provides an audit trail for later review and feedback.

VRSs located in Quebec City, Toronto, and Victoria have been networked together. Experienced officers successfully performed formation manoeuvres interactively within a common virtual environment as if they were 300 yards, rather than 3000 miles, apart. The cost of this type of training with conventional simulators would be prohibitive. The MARS VRS software has been licenced to two Canadian firms for national and international sale.

The Flight Simulation Facilities of DLR

1. Name of Facility and Location

Deutsches Zentrum für Luft- und Raumfahrt e.V.
(German Aerospace Center)
Institute of Flight Research
Lilienthalplatz 7
38108 Braunschweig
Germany

2. General Facility Description

- ATTAS (Advanced Technologies Testing Aircraft System) based on a VFW-614 2-Jet engine plane of 20 tons as test and research aircraft with "Fly by Wire" and "Fly by Light" technology.
- ACT/FHS (Active Control Technology/Flying Helicopter System) based on an EC-135 helicopter as test and research rotorcraft with "Fly by Light" technology.
- ATTAS ground based simulator with fix based cockpit and sound simulation.
- ACT/FHS and BO105 ground based helicopter simulation with fix based experimental cockpit.

3. Main Technical Data (only Ground-Based Simulation)

- Visual System (for helicopter simulation)
  - Hardware: ONYX RE3, Indigo 2, Octane
  - Projection System: 2-channels
- Computer equipment
  - ADI RTS (Real Time Station) VMEbus-based, Compute-Engine: Power-PC 2604
  - ADI RTS, Compute-Engine Power-PC 604
  - Multiprocessor VMEbus-Systems (68060)
  - Data General computers
  - SUN and SGI workstations
  - Personal Computers
- Cockpit description
  - ATTAS cockpit with aircraft identical test equipment for the test pilot (left hand side), generic instrumentation for the safety pilot (right hand side).
  - Helicopter cockpit with rotorcraft identical equipment (right hand side), generic instrumentation for the safety pilot (left hand side).

4. Simulation Activities

- Development and operation of a transport aircraft In-flight Simulator ATTAS and a helicopter In-flight Simulator ACT/FHS for research and demonstration purposes. The hardware of the in-flight simulator aircraft is designed in cooperation with the industry (DASA and ECD/ECF). The experimental system and in-flight simulation techniques are developed and approved by the DLR.
- Development and operation of a ground-based transport aircraft simulator as system simulator for ATTAS, a ground-based helicopter simulator as system simulator for ACT/FHS and as a BO105 helicopter simulator. The facilities are developed and installed at DLR. All hardware components are integrated by the DLR. Model specific software components are generated by the DLR.
- The ground-based simulators are normally used as test tools for preparing flight test tasks with the in-flight simulators. Soft- and Hardware for all the different experiments running onboard during flights with the real aircraft are first tested on the ground with the realtime system-simulators.
- Test Pilots training is another important task for the simulators as well as testing of newly developed hardware components such as sidesticks and displays..
- The ground-based facilities are used for realtime simulations of subsystems and any kind of dynamic systems.
- Generation and validation of simulation data bases by system identification techniques
- Cooperation with the ZFB, Berlin, to use the A340 Full Flight Simulator for research purposes.

5. Outstanding Points of the System and Limitations

- Most realistic simulation of transport aircraft and helicopters with the in-flight simulators ATTAS and ACT/FHS including motion and visual impression.
- Best performance for demonstration of avionic equipment.
- Limitations may be given by the dynamics of the host aircraft and helicopter.
- Large scaled ground-based simulators with high flexibility of interfacing external hardware components. High level of simulation fidelity of models due to the demands of system simulations.
- No motion simulators.

6. Future Developments

- Installation of a new ground-based helicopter simulator to be operated as a system simulator for the new ACT/FHS in-flight simulator and as a high flexible simulator for any kind of rotorcraft including different model libraries.
- Model enhancements for the ATTAS system simulator, generation of a model library.

Universität der Bundeswehr Hamburg
Institut für Kraftfahrwesen und Kolbenmaschinen
Holstenhofweg 85, D-22043 Hamburg, Germany
Tel.: 049 +40-65412159 Fax.: 049 +40-65412742
Internet: http://www.unibw-hamburg.de/MWEB/ikk/fkw/s-2.html

ORSIS - Off Road Systems Interactive Simulation

ORSIS (On and Off Road Systems Interactive Simulation) is a realtime simulation, which can be operated interactively (e.g. free choice of course, driving direction and speed) by a driver. The program is based on detailed physical vehicle modelling (eg. propulsion systems, suspension, steering system, control effectors) and a realistic terrain model (digital map with altitudes, stochastic unevenness, local strength properties including natural scattering and weather impact). Furthermore it includes the various vehicle soil interactions (e.g. sinkage, slip sinkage, tire deflection, rolling resistance, traction, multipass, obstacle passage).

The sight from the drivers seat is visualised. ORSIS provides a great variety of results (e.g. speed, accelerations, torques and loads on vehicle components, cooling heat, fuel consumption).

Therefore, the simulation program is a tool for vehicle development as well as for mission planning. The latter specially is important for out-of-area military missions due to the possibility to integrate any terrain. In combination with a driving simulator, ORSIS allows a very realistic driver training especially in dangerous conditions and in heavy terrain.

ORSIS – OpenGL view

VENUS – VEhicle NatUre Simulation

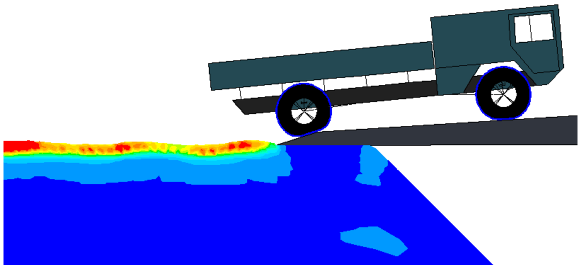
VENUS is used to investigate in detail the phenomena of wheel-soil interactions. The concept, based on the Finite-Element-Method, is characterised by substructure models for the soil and for the tire. In addition the vehicle structure with its main components can be included.

Using the FEM, the sinkage and the deflection of the wheel, the pressure distribution in the ground and especially the contact shape between the elastic wheel and the deformed and compacted soil are gained as simulation results also in case of an oscillating vehicle.

VENUS is established on the commercial FEM program ABAQUS. The soil behaviour is described with the elastic-plastic material law *Modified Drucker Prager / Cap Model*. For the investigation of the dynamic vehicle-ground interaction, an explicit dynamic solving algorithm, available with ABAQUS / Explicit, is used.

Fields of application

wheel-soil interaction, influence of tire-profile on traction and rolling resistance, vertical vehicle dynamics investigation of ground deformation and compaction due to dynamic wheel-loads .



ADAMS-STINA

STINA (Soil Tire Interface to ADAMS) is a supplementary tire-ground interaction model for ADAMS, which allows to investigate the vertical dynamics vehicles on uneven deformable ground. STINA considers the classic method of wheel-soil interactions integrated in the multibody-program. It calculates the vehicle oscillations, the deformations of elastic tires and the deformation of the unevenness regarding the soft ground.

Main features

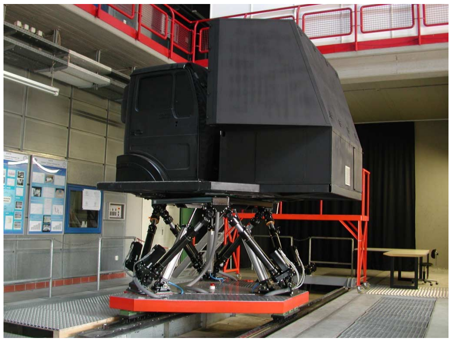
- Dynamic soil behaviour
- Tire inflation pressure
- Multipass effects
- Graphical user interface

Fields of application

Dynamic loads on deformable, uneven ground, Effects of dynamic wheel loads on track profile

MARS

The driving simulator MARS (Modular Automotive Research Simulator) is a research tool to investigate the demands for motion systems under on- and off-road driving conditions. The motion system consists of an electrical driven 6-DOF-system for simulating all 6 degrees of freedom and especially the inclination angels. An additional actuator is installed for realising sudden transversal movements, which occur for example in lane change manoeuvres. A main aspect is the testing of possibilities to reduce the movements of the system. Here the thresholds of perception of the human being, the interaction of the vestibule and the visual information and the influence on the perception in case of superposition of different movements are of great importance.



Simulator MARS

Fields of application

Physiological and psychological tests, development of assistance systems, autonomous driving, development of motion systems, off-Road driving simulation

PAISI

PAISI (Power and Inertia Simulator) is a performance test facility for vehicles and vehicle components.

Technical Characteristics

- Two electrical DC-machines (each with a continuous / peak power of 400 / 600 kW)
- Operation in motor and generator state respectively, forward and backward
- Torque control, speed control
- Automatic resistance simulation including turning resistance of tracked vehicles
- Dynamic testing

Fields of application

Testing of complete drive lines, brake systems, engines, gears and clutches,

Institute for Marine Dynamics
P.O. Box 12093
St. John’s, Newfoundland
Canada A1B 3T5

Fax: +1 709 772 2462
http://www.nrc.ca/imd/

Contact: Noel Murphy, Business Development Office
Tel: +1 709 772 4939

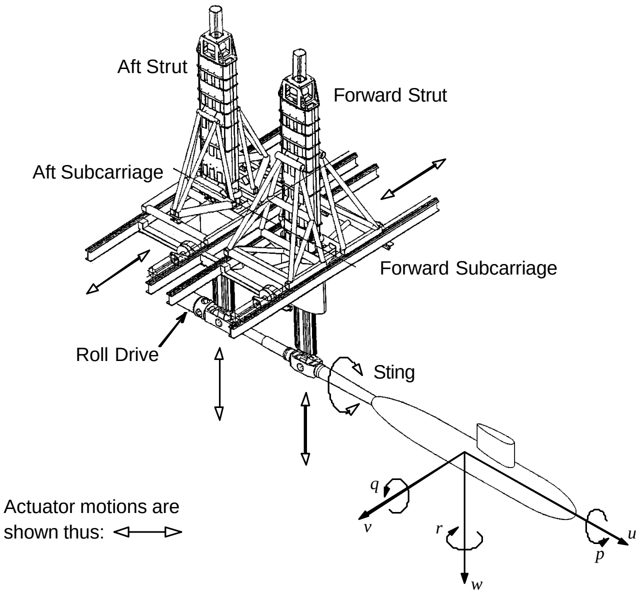
1. Overview

The Institute for Marine Dynamics (IMD) was established to provide innovative solutions and technical expertise in support of Canadian ocean technology industries. It employs numerical, model and full scale studies to predict or evaluate the performance of a range of systems in the ocean environment, and has helped to commercialize vessel prototypes, underwater systems, ice detection equipment, and more.

General facilities available for model testing include the 200×12×7 m towing tank, the 90×12×3 m ice towing tank, the 75×32×3.2 m offshore engineering basin, and a small cavitation tunnel, as well as machine shops capable of manufacturing ship models up to 13 m long.

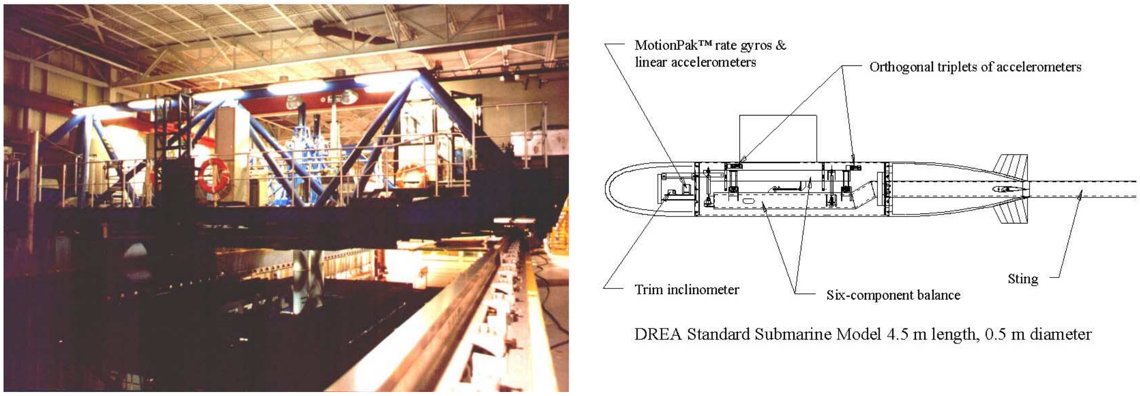
2. Marine Dynamic Test Facility (MDTF)

The MDTF represents a new generation of dynamic testing apparatus. This device imparts large amplitude (± 1 m) and high rate (± 1 m/s) arbitrary motions to a subsurface or surface model in up to six



Marine Dynamic Test Facility general arrangement.

degrees of freedom. Underwater models up to 6 m long and surface models (using the vertical struts connected directly to hardpoints on the model) up to 9 m long can be tested. To take maximum advantage of its capabilities requires new approaches to experimental design and extensive use of SI techniques. The model contains a 6-DOF balance to measure total forces and moments; the control appendages may also be instrumented. An internal propulsion dynamometer is used for propulsion experiments, requiring the model to be supported by the alternative twin-strut arrangement.



DREA Standard Submarine Model 4.5 m length, 0.5 m diameter

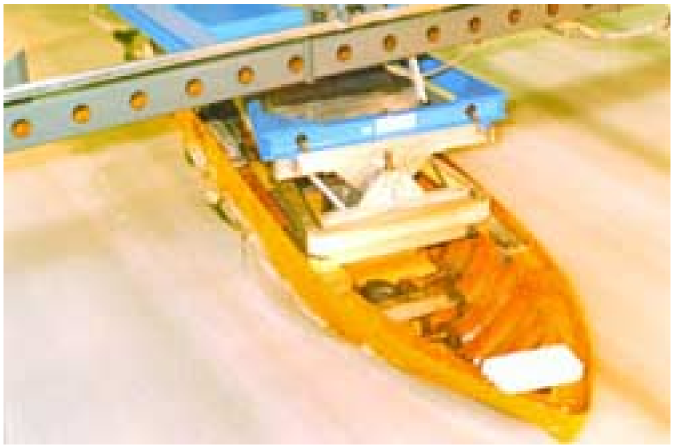
Left, MDTF on the towing tank carriage. Right, sting-mounted submarine model with internal balance.

Reference C.D.Williams, M.Mackay, C.Perron, and C.Muselet: "The NRC–IMD Marine Dynamic Test Facility: A Six-Degree-of-Freedom Forced-Motion Apparatus for Underwater Vehicle Testing", International UUV Symposium, Newport RI, April 2000.

3. Horizontal Planar Motion Mechanism (HPMM).

The HPMM is a large amplitude planar motion mechanism used for manoeuvering studies of surface vessels in open water or ice. Sway (lateral) amplitude is ± 4 m at up to 0.65 m/s, yaw rates up to 60 deg/s.

Reference D.S. Spencer and F.M. Williams: "Development of a New Large-Amplitude Planar Motion Mechanism at IMD", 25th American Towing Tank Conference, Iowa City IA, September 1998.



Icebreaker model mounted on the HPMM on the ice towing tank carriage.

The Flight Evaluation Facilities of NRC

1. Name of Facility and Location

Flight Research Laboratory, Institute of Aerospace Research
Building U-61
Ottawa, Ontario, Canada, K1A 0R6
General contact: stephan.carignan@nrc.ca (613) 998-5524 / (613) 952-1704 (fax)

2. General Facility Description


Bell 412 Advanced Systems Research Aircraft

The Bell 412 Advanced Systems Research Aircraft (ASRA), a fully programmable, full authority fly-by-wire helicopter, capable of possessing a wide variety of dynamic characteristics and avionics systems with the performance engendered by a four bladed "soft-in-plane" rotor system and twin engines.


Bell 205 Airborne Simulator

Bell 205 Airborne Simulator – a fully programmable, full authority fly-by-wire helicopter based on a Bell 205a, capable of possessing a wide variety of dynamic characteristics and avionics systems.


Falcon 20 HUD Research Facility

A Falcon 20 aircraft fitted with enhanced navigational systems and a research dedicated Heads-Up Display complete with enhanced vision sensors and programmable symbology.


Harvard Display Evaluation Research Aircraft

A Harvard aircraft fitted with a fully programmable pilot display system in the rear cockpit for evaluation of new display concepts.

3. Main Technical Data

- Both research helicopters have VME based data acquisition and flight control computers with comprehensive safety monitoring.
- Bell 412 has on-board PC based engineering workstation for full experimental control.
- Bell 205a features a fully programmable digital artificial feel system allowing for the simulation a variety of pilot inceptor qualities and force feedback cues.
- Bell 205a features a Three Axis Stabilized Table (TAST) for camera mounting, enabling research into helmet mounted displays and enhanced and synthetic vision systems.
- PC based data playback with time domain and frequency domain analysis tools.
- Harvard has a real-time data acquisition system based on Labview software with a configurable display based on the VAPS virtual prototyping system.
- Falcon 20 utilizes advanced guidance systems based on differential GPS systems and inertial data

4. Simulation Activities

- Handling qualities for the helicopter ship deck-landing task.
- Tactile cueing and carefree handling for helicopters for improved safety of helicopter operations.
- Modern control law research for helicopters where new control methodologies such as H-infinity are testing in-flight.
- Variable stability helicopter course for various test pilot schools.
- Handling qualities of helmet mounted displays, including symbology, field-of-view, effects of transport delay and roll compensation.
- The Harvard will be used for flat panel symbology evaluation in unusual attitudes and HMD attitude symbology evaluation.
- Falcon 20 is used for runway friction and approach guidance evaluations. It will be used to determine basic operational and approach procedures for HUD equipped transport aircraft that use enhanced vision systems.

5. Outstanding Points of the System and Limitations

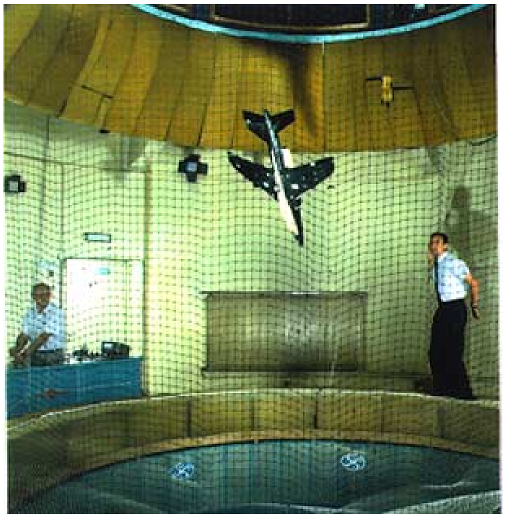
- Both helicopters are highly versatile research platforms allowing fast and easy changes to configuration for greater flexibility.
- ‘Real’ visual and motion cues are provided during in-flight simulation in a realistic operation environment.
- Dynamics of the simulation is limited by the characteristics of the host vehicle.
- Harvard is an aerobatic aircraft that allows inexpensive in-flight evaluation of symbology with veridical motion, visual and vestibular cues.
- Limited to working with in the flight envelope of a piston-engine aerobatic aircraft.
- The Falcon 20 is representative of small business and transport category aircraft, and has a long history of collaborative work with international regulatory agencies.

6. Future Developments

- Installation of rotor state feedback system on Bell 412 ASRA.
- Continued improvement in the Bell 412 dynamic models for simulation and control system design.
- Development of on-board real-time data analysis capability for the Bell 412 ASRA.
- Installation of a digital force feel system and active sidestick system in the Bell 412 ASRA.
- Integration of a helmet-mounted display system on the Harvard.
- Upgrade of the data acquisition system and integration of an infrared enhanced vision camera with the HUD.

Systems Control and Flight Dynamics Facilities at ONERA

- ***Vertical Wind Tunnel*** :
  This vertical tunnel is a closed circuit, open test section, continuous flow and low speed tunnel.
  Facility for spin prediction studies and for dynamic stability parameter identification by means of a rotary balance.
  Dimensions : 4m circular
  Maximum velocity : 50m/s
  Spin test : free flight test of radio remote controlled models Identification of spin modes. Spin tests are performed in Froude similitude.
  Rotary balance : Steady and unsteady aerodynamics at high angle of attack, including the dynamic stall phenomenon. Coning and Oscillatory coning motions are simulated.
  Point of Contact: Olivier Rénier
  ONERA Centre de Lille
  5, Boulevard Paul Painlevé,
  59045 LILLE Cedex
  France

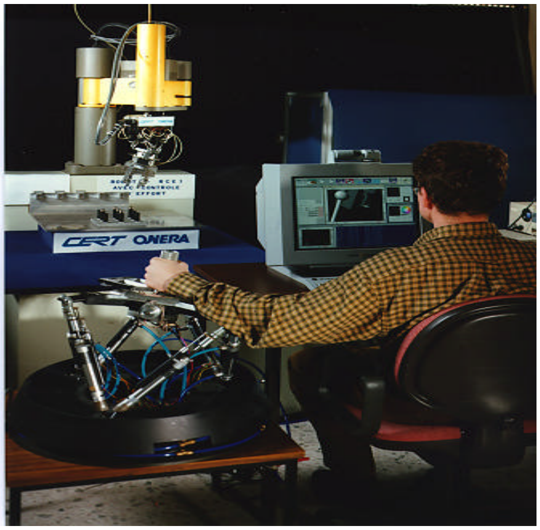


- ***Flight Analysis Laboratory*** :
  In this laboratory instrumented models are catapulted in free flight. The facility is used for modeling of aircraft behavior in turbulence, in ground effect, and for identification of dynamic parameters in flight.
  Generally, tests are performed in Froude similitude
  The facility housed in a special building include :
  - a catapult to launch model in free flight
  - a vertical wind tunnel to generate vertical gusts along the free flight path of the model ;
  - a lateral wind tunnel to generate lateral gust
  - a removable platform in order to study landing and ground effects and crash of air vehicles.

  Model size : 3m in span length maximum
  Maximum Velocity : 45m/s
  Max Usable Flight Path Length : 25m
  Point of Contact: Jean François Lozier
  ONERA Centre de Lille
  5, Boulevard Paul Painlevé,
  59045 LILLE Cedex
  France

- ***Remote Manipulation Facility***:

  This facility aims at developing and assessing control techniques and technologies in space and aeronautical fields. For flight simulation, kinesthetic feedback on the stick can be tested and studied.
  Sticks: 3 or 6 degrees of freedom stick with hybrid control allowing force or position feedback
  Real time processing
  Point of Contact: Claude Reboulet
  ONERA Centre de Toulouse
  BP 4025 2,Avenue Edouard Belin
  31055 TOULOUSE Cedex
  France



- ***SECAFLEX Test Bench*** :

  Two different experimental setup are used to design and optimize active control of flexible structures
  - One first is compounded of two flexible beams controlled by electric motors
  - The second flexible setup is a truss beam with embedded piezo electric translator.
  Dimension: about 4m in length
  Pneumatic suspension
  Point of Contact: Jean Pierre Chrétien
  ONERA Centre de Toulouse

- ***Interaction Pilot-System Laboratory (LIPS) :***

  This facility is used for research activities in :
  - flight mechanics : handling qualities criteria, evaluation of control law algorithms;
  - human factors : analysis of pilot activity for aircraft safety purpose.

  Computer: SGI ONYX RE2 and Workstation SGI Indy
  Control System : Flybox (B.G System) ; mini-stick 3 d.o.f and 2 hand-levers
  Visual System: CGI
  Point of Contact: Thanh Huynh
  Laboratoire de Recherche ONERA
  Base aérienne 701
  13661 SALON AIR Cedex
  France

The Flight Simulation Infrastructure of the NLR

1. Name of the Institute and Location

Nationaal Lucht- en Ruimtevaartlaboratorium NLR
(National Aerospace Laboratory NLR)
Flight Division
Anthony Fokkerweg 2,
1059 CM AMSTERDAM
The Netherlands

Contact:
Head Flight Simulation Dept.
Ir. W.G. Vermeulen
E-mail: wimsim@nlr.nl
Phone: +31 205113587/3586
Fax: +31 205113210
Or visit our website: www.nlr.nl

2. General information

The Flight Simulation Infrastructure of the NLR is operated at NLR's site in Amsterdam and is operated by the Flight Simulation Department of the NLR. The Infrastructure consists of a whole range of flight simulators for research, from desktop pilot stations to full mission simulators that can offer the pilot a very realistic experience of flight. The Flight Simulation Infrastructure further offers the possibility to record all kinds of data, including physiological data of the human subjects.

The full mission simulators are the "National Simulation Facility" (NSF) and the "Research Flight Simulator" (RFS). The NSF and the RFS are flight simulators with motion and visual systems, which provide the pilots with a very realistic flight environment, including all sensations and complexities that are present in real flight. The Flight Simulation Infrastructure, which became operational in 1974, has gradually extended its capabilities. Other components have been procured later: the 6 degrees of freedom motion system and the image generator for the out-the-window-view, for example, were procured in 1985 in 1991 respectively. The Flight Simulation Department of the NLR employs 25 permanent staff to operate, develop and maintain the infrastructure. To support research projects on the Flight Simulation Infrastructure, approximately 30 NLR staff give support in areas such as Human Factors, Flight Mechanics, Air Traffic Control and Flight Deck Design.

3. Components of the Flight Simulation Infrastructure

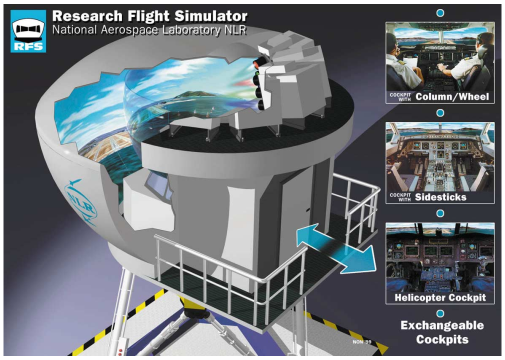
The flight simulation infrastructure consists of two full mission research simulators: the "National Simulation Facility" (NSF) and the "Research Flight Simulator" (RFS) as well as desktop and generic fixed based pilot stations. Moreover all required supporting measurement tools are available.

The National Simulation Facility NSF

The Research Flight Simulator RFS

Currently, the NSF is configured with a F-16 MLU cockpit in a 17ft dome display system. The F-16 MLU cockpit is fitted with a dynamic seat that can provide additional motion cues. The projector that projects the simulated out-the-window-view, follows the head movements of the pilot. For research purposes, a fully adjustable control loading system with a centre stick can be fitted in the F-16 MLU cockpit. The combination of a high quality motion system with the wide field of view visual system and the physiological measurement suite make the simulation facilities unique for research into human perception, handling qualities of aircraft and Human-Machine Interface.

The F16-MLU cockpit with simulated out-the-window-view of the NSF



The RFS - NG

The RFS uses a 4 degrees of freedom motion system and a generic transport aircraft cockpit. The RFS is currently being upgraded to the RFS-NG, which will include a new reconfigurable cockpit (Boeing or Airbus configuration). The RFS-NG will use a 6 degrees of freedom motion system and will have a wide field of view display system. The RFS-NG can be interfaced with NLR's ATC simulator (NARSIM) to provide a complete simulation of air and ground interaction. Two fixed based pilot stations (one for fighter simulation and one for helicopter applications) and desktop flight simulators are also available for experiments or for participation in scenarios with the RFS and the NSF.

Fighter Pilot Station with Eye Tracker

The Helicopter Pilot Station (HPS)

4. Capabilities

A variety of fixed and rotary wing aircraft can be simulated with the facilities; for example the BO105, the SA-330 Puma, the CH-47D Chinook, the NH-90, the B747, the Fokker-100, Fokker-50, Cessna Citation and Fairchild Metro II. Apart from the Lockheed-Martin F-16, other fighters have also been simulated, but these models can not be used by third parties due to their classification. Simulation models can be modified and new models can be easily implemented. All variables of the simulation model can be logged for evaluation purposes. Measurement of human physiology is standard (eye tracking, respiration rate, heart rate).

The research staff of the NLR is very experienced in human factors, training and flight mechanics research and has a great deal of experience in doing research in those areas, using the Flight Simulation Infrastructure. They can thus guide users through the design, implementation, execution and processing of an experiment that uses parts of NLR's Flight Simulation Infrastructure.

The Ground Vehicle Simulation Facility at TACOM

1. Name of Facility and Location

U.S. Army Tank-automotive and Armaments Command (TACOM)
Ground Vehicle Simulation Laboratory
Building 215, Mail Stop #157
Warren, MI 48397-5000

2. Facility Description

The Ground Vehicle Simulation Laboratory (GVSL) is located at the U.S. Army Tank-automotive and Armaments Command's (TACOM) Tank-Automotive Research, Development and Engineering Center (TARDEC) in Warren Michigan. This world-class facility for ground vehicle performance simulation and durability assessments is ideally suited to evaluate new technology and vehicle system design changes and upgrades. It consists of four unique full-scale high-performance motion base simulator systems. They are the Ride Motion Simulator (RMS), Crew Station/Turret Motion Base Simulator (CS/TMBS), the Pintle Motion Base Simulator (PMBS) and Reconfigurable "N"-Post Simulator (RNPS). These simulators are utilized to subject vehicle systems, sub-systems and or occupants to a variety of dynamic environments, which accurately emulate motions and disturbances comparable to those experienced in typical proving ground tests or field operations. In addition to the motion base simulators, the GVSL is home of the Vehicle Inertial Properties Evaluation Rig (VIPER) used to measure the mass and inertial properties of both wheeled vehicles and combat vehicle turret systems.

3. Assets and Capabilities

The GVSL PMBS and RNPS simulator assets are capable of conducting durability and structural reliability assessment on entire vehicle systems, subsystems, components and or payloads. Typical applications have been:

- Durability assessments of improved structural components for truck and trailer systems.
- Durability assessments of new and improved mission payloads.
- Cyclic durability testing of suspension systems.
- In vehicle Road Load Data Acquisitions (portable data acquisition).
- Vehicle structural mode characterization for truck and trailer systems.

The GVSL VIPER asset is capable of measuring the mass properties of most military vehicle systems and payloads. These mass properties can then be used to build accurate vehicle dynamics models to explore performance issues such as vehicle stability, roll over, mobility and transportation. Typical applications of the VIPER have been:

- Measure the mass properties of truck and trailer systems.
- Measure the mass properties of payload and turret systems.

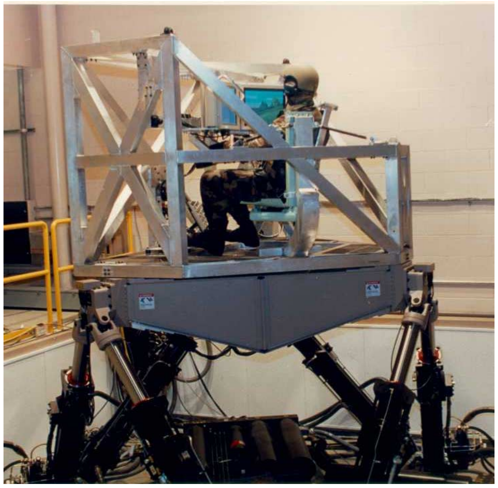
The GVSL RMS and CS/TMBS simulator assets are specifically designed to provide highly controlled motion environments for both hardware and human performance evaluations. Typical applications have been:

- Measurement of target tracking ability of differing controls for Advanced Technology Demonstrators
- Characterization of human body/seat dynamics for different vehicle systems.
- Assessment of the effect of mass and mass imbalance on different traverse drives motors for turret systems.
- Performance comparison of different gyroscopes in turret weapon stabilization systems.

4. Simulation Contact

Point of Contact: For technical and budgetary matters concerning GVSL experiments, please contact either Aleksander Kurec, 810-574-7583, kureca@tacom.army.mil or Harry Zywiol, 810-574-5032, zywiolh@tacom.army.mil. Specific past experiences can be provided upon request.

Ground Vehicle Simulation Facility

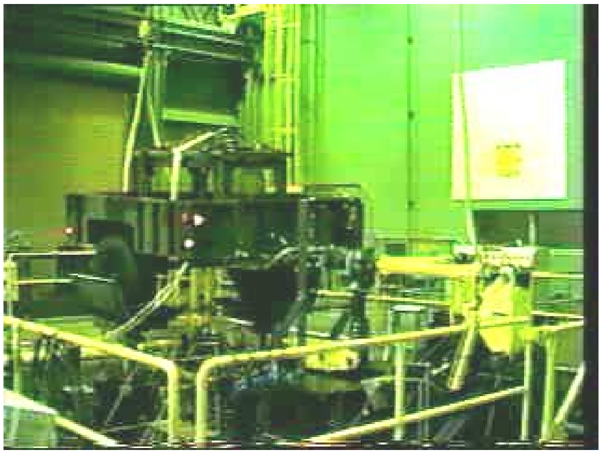


Ride Motion Simulator

Vehicle Inertial Properties Evaluation Rig

Reconfigurable “N” Post Simulator

Turret Motion Base Simulator



Pintle Motion Base Simulator

University of Toronto Institute for Aerospace Studies

Institute for Aerospace Studies
4925 Dufferin Street
Toronto, Ontario
Canada M3H 5T6

Tel: +1 416 667 7700
Fax: +1 416 667 7799
http://www.utias.utoronto.ca

Contact: Prof. L.D. Reid, Flight Simulation Group (tel: 416 667 7705)

Flight Research Simulator

This facility is intended for research into simulation techniques and man/vehicle interaction studies. The cab is mounted on a state-of-the-art six degrees-of-freedom motion base and its interior contains both a jet transport cockpit and a general purpose work station which can be quickly modified to represent a wide range of both ground-based and flight vehicles. The simulator is operated by a network of digital computers. The forward view visual display employs infinity optics and is based on computer generated imagery. Either a helmet mounted fiber-optic display or window units can be employed.

Recent Research

- Simulation of Helicopter Deck Landings
- Simulation with Reduced Motion System Degrees-of-Freedom
- Enhanced/Synthetic Vision Systems

The Variable-Stability In-Flight Simulator Test Aircraft (VISTA) NF-16D USAF Test Pilot School, Edwards AFB

1. Name of the Facility and Location

USAF Test Pilot School, Plans and Programs (USAF TPS/XP)
220 S. Wolfe Ave.
Edwards, CA 93524
Contact: Major Andy Thurling
661-277-6554

2. General Facility Description

The Variable-Stability In-flight Simulator Test Aircraft (VISTA) NF-16D is a unique national development, test, evaluation, and training asset owned by the United States Air Force (USAF). The VISTA is managed by the USAF Test Pilot School and operated by Veridian Flight Research personnel at Edwards Air Force Base, California. VISTA provides research and development, evaluation, and in-flight simulation capabilities for guidance, navigation, and control (GN&C) systems and cockpit display research and development. By using VISTA, the entire aerospace vehicle system (which includes simulated aircraft dynamics, guidance, navigation, flight control laws, ground stations, communication links, etc.) can be tested in a real world flight environment without risking an actual test vehicle or compromising test results. Higher risk testing including unproven or unconventional control concepts, system failure and reversion modes, sensor, propulsion or actuation system failure modes, safe modes, and auto-land can be performed without increased risk due to the presence of an on-board safety pilot. Full-fidelity risk-reduction testing can demonstrate that a new system functions properly and provide added confidence prior to first flight.

3. Main Technical Data

The VISTA NF-16D aircraft has unique flight research test-bed and in-flight simulation capabilities that make it an ideal test bed. The fight research capability is provided by many on-board systems that are unique to the VISTA flying test-bed including: fully programmable flight control and avionics computer systems, fully programmable variable center-stick and side-stick feel systems, fully programmable Multi-Function Display (MFD), Head-Up Display (HUD) and Helmet-Mounted Display (HMD) systems, a voice recognition system, and significant provisions (power, cooling, and Mil-Std-1553 busses, etc.) for customer supplied hardware flight testing capability, in-flight refueling (both probe/drogue and boom/receptacle type) systems, weapon systems flight test, a fully accessible and programmable instrumentation system, and provisions for an axi-symmetric thrust vectoring system. The VISTA aircraft configuration consists of several unique features specifically installed for its mission as a flying test bed. A list of some of these features is given below:

- NF-16D, S/N 86-0048
- Block 30 airframe, Peace Marble II configuration, including large dorsal fairing for additional equipment
- Pratt and Whitney F100-229 engine with wide inlet
- Heavyweight landing gear
- Heavier wing carry-through structure
- Block 40 avionics and Digital Flight Control Computer (DFLCC)
- GEC/Marconi Viper-II HMD
- Wide field of view HUD
- APG-68 targeting radar
- Dry hook-up utilizing the probe/drogue system while in the Variable Stability Mode
- Provisions for a P&W Axi-symmetric thrust vectoring nozzle
- Nine external store stations for tanks, pods, and weapons with programmable digital interface to each station
- Integration of the weapon system with the programmable avionics, display and flight control systems

4. Simulation Activities

In-Flight Simulation (IFS) is the process of augmenting a "host" aircraft, the VISTA, through a control system to simulate the flight characteristics and dynamics of another aircraft. The actual GN&C system of the "simulated" aircraft is implemented in the "host" aircraft during the in-flight simulation. Subsequently, the characteristics of the "simulated" aircraft can be tested and evaluated in a real world environment. In this way specific flight control system changes (e.g., failure modes, gain changes, and control system testing) can be evaluated. All inputs to the GN&C can be provided including ground or airborne based commands, GPS, and inertial and body axis measurements. In addition, telemetry up and down links can be provided, if necessary.

Flight-testing and in-flight simulation are conducted using the Variable Stability System (VSS). The VSS is a digital and analog system that interfaces with existing F-16 avionics and sensors (in addition to custom VSS sensors). Some primary components of the VSS include:

- Two identically configured VME 64X based 233 MHz Pentium computers (VSS1 and VSS2) connected to six MIL-STD 1553B data busses.
- One VME64X-based 200 MHz Pentium Feel System Computer (FSC).
- Programmable Variable Feel Center-Stick and Side Stick
- Programmable Display System (including MFD, HUD and HMD).
- Engage Logic and Interface Chassis (ELIC).
- Custom VSS Panels and Displays
- Sensor Conditioning Chassis (SCC).

All of the VSS computers can be programmed using Ada, FORTRAN, or C and using rapid prototyping methods such as Matlab/Simulink and Matrix X autocode generation. Because of the parallel presence of an independently verified and validated set of F-16 flight control laws and real time monitors, the VSS is not a safety-of-flight critical system and changes to the system therefore do not require extensive verification and validation testing. This makes the VSS a useful tool for rapid prototyping and allows quick turnaround of desired system changes.

A summary of VISTA's flight envelope with the Variable Stability System engaged and capabilities are presented below:

Maximum airspeed:	440 KIAS / 0.9 Mach
Angle-of-attack limits:	-10° to +16°
Normal load factor limits:	-2.4 to +6.8 gs
Maximum sideslip:	±10°

- Up to 300 knot approach speeds
- Touchdown speeds up to 220 knots
- Minimum L/D ~2

Flight duration varies from 1.2 hours with a clean configuration to 1.6 hours with a centerline tank installed; in-flight refueling can extend flight time if required. Due to built-in safety and redundancy features, VISTA is also one of the few in-flight simulation aircraft that is capable of landing while the VSS is engaged allowing customer configurations to be tested through touchdown. Multiple approaches can be accomplished on any flight with the potential for back-to-back comparisons, variations in aerodynamics characteristics, failures or modifications to be completed on each flight test.

5. Outstanding Points of the System and Limitations

VISTA's outstanding points are clearly illustrated above. VISTA's one limitation is that the vehicle is used for TPS syllabus flights and test projects must coordinate with TPS scheduling. Integration with the TPS schedule has not been difficult thus far. TPS is committed to keeping the VISTA as a world-class research and development aircraft available for a variety of projects and customers. These include UAV testbed work, avionics and display research, hardware integration testing, human factors studies, specification research, and aircraft development programs.

6. Future Developments

VISTA refinement is an ongoing process. Future plans include developing a second HMD as well as adding fly-by-wire throttle control. Thrust vectoring for use under VSS control is also a possible future addition.

Appendix II

Intelligent Transportation Systems (Land Vehicles) Overview of the State of the Art

A. Vehicle System Control

B. Component Control

C. Driver Assistant on Board

D. Telematic Information System

There are many new devices, components and systems that have been or are being developed to provide vehicle and driver aids thereby making intelligent automotive transportation possible. In general, these new technologies are first available for personal cars use, and subsequently, when applicable, they are made available to the commercial trucking industry. These intelligent systems and driver's aid may also be of interest to the military, however, their application with regard to military requirements will not to be considered here.

The following four sections summarizes the state-of-the-art, development and application of intelligent vehicle systems technology. This information was gathered from the presentations and proceedings of the SEOUL 2000 FISITA WORLD AUTOMOTIVE CONGRESS entitled "Automotive Innovation for the new Millennium", held 12-15 June, 2000. The sessions on "Intelligent Transportation Systems (ITS)" were of particular interest in this regard (The Program of this Automotive Congress is attached).

A. Vehicle Control Systems

These systems pertain to vehicle driving control

Item	**Status**	**Application**
Constant speed control	Available	personal cars
Following Distance control	Available	personal cars
Parking collision warning	Available	personal cars
Anti wheel locking (ABS)	Available	personal cars and commercial trucks
Automatic Traction Control (ASR)	Available	personal cars and commercial trucks
Electronic Stability Control(ESP,DSC,ESC)	Available	personal cars and commercial trucks
Collision Avoidance System	Under development	
Vehicle lane tracking	Under development	
Automatic highway entrance and exit	Under development	
Intelligent speed adaptation	Under development	
Hands-free systems	Being considered	
Autonomous vehicle control	Trend	

B. Component Control

Item	**Status**	**Application**
Automatic drive-line management	Available	personal car / commercial trucks
Automatic gears	Available	personal car / commercial trucks
Automatic differential locking	Available	personal car / commercial trucks
Fuel injection control	Available	personal car / commercial trucks
Emission control	Available	personal car / commercial trucks
Semi (active suspension)	Available	personal car / commercial trucks
Air bag activation	Available	personal car / commercial trucks
Automatic seat positioning	Available	personal car / commercial trucks
Automatic climate control	Available	personal car / commercial trucks
Diagnostics on board	Available	personal car / commercial trucks
Head light direction control	Available	personal car
Automatic tire inflation pressure control	Under development	
Automatic front and rear collision avoidance	Under development	
Active noise control	Being considered	
Intelligent tire	Being considered	

C. Driver Assistant on Board

Item	**Status**	**Application**
Autopilot system/route guidance	Available	personal cars and commercial trucks
Automatic braking assistant	Available	personal cars
On-board office	Available	personal cars
On-board diagnostics	Available	personal cars
Picture of road ahead and behind on monitor	Under development	
Night vision assistance	Under development	
Preview of curves and obstacles	Under development	
Car drivers partner assistance	Under development	
Real time route guidance	Under development	
Navigation map with exact data base (2000 : 5,0 m/2005 : 1,0 m/2010 : 0,1 m)	Under development	
Automatic update of navigation map	Being considered	
Internet Access	Being considered	
Emergency Call message	Being considered	
Any important information	Being considered	

D. Telematic Information Systems

- Adaptive cruise control, stop and go traffic light control
- Parking guide systems
- Real time traffic, floating cars real-time route guidance
- Traffic sign regulation with transmission into vehicles
- Integration of all transportation modes
- Automatic accident reporting
- Emergency Call Message
- Commercial fleet management/freight management
- Navigation map with detailed data base
- Current Up-Date of navigation base automatically
- Extremely high accuracy of vehicle localisation via satellite
  (today: 5 m; 2005 : 1,0 m; 2010 : 0,1 m)

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Appendix III

Crew Stations and Steering Elements in Main Battle Tanks

III.1 Driver

Drivers of land vehicles operate in an essentially two-dimensional world. Steering controls are required for directional control (left-right), for forward-reverse, and for regulating speed (both controlled acceleration and deceleration). Because the terrain ahead is not homogeneous, flight path predictors, such as those found in Heads-Up Displays (HUD) of modern aircraft, are not feasible. For the same reason, neither are corner speed predictors that are found on aircraft HUDs. Modern land combat vehicles can virtually never generate enough lateral acceleration to roll over on even grounds, but a roll-over warning system might be useful for Tactical and Administrative Use vehicles. Slip indicators and slip control devices (ABS, ASR) as well as automatic directional stability systems are generally not yet fitted. However, on vehicles with distributed drive trains (such as electric drive vehicles with in-hub motors), slip control would allow power to be redistributed to maximise traction for either braking or acceleration in a much more efficient way than is currently possible through the use of limited-slip differentials and fluid couplings. Tire inflation pressure is manually controlled in some vehicle types, however so far an automatic tire inflation pressure control e.g. one activated by slip, does not yet exist. The same is true for automatic differential lock control.

Precise directional control is required not only for negotiating (or avoiding) obstacles, but also for loading the vehicle on to rail cars or aircraft. It is not unusual for tanks to be loaded on railcars whose width is less than that of the tank, so the tracks hang over the edges of the car on both sides by as much as half their width. All kinds of Combat and Tactical vehicles are routinely transported on aircraft whose cargo bay width is only a few inches wider than the vehicle. The following sections describe the few main types of steering control.

III.1.1 Laterals – This is the oldest type of control. It was developed as a simple all-mechanical means of applying brakes to the powered shafts of tracked vehicles. (This type of control is still found on bulldozers.) Up until the 1950’s tracked vehicle layout almost universally put the engine in the back, and the transmission in the front. Thus the driver was located in such a way that direct mechanical linkages to the transmission and final drives were available.

A US Sherman (Figure III.1) displays the layout common during WWII. In later designs, power assist was added to reduce driver effort, but the basic layout has been little changed otherwise. Braking the vehicle is accomplished by applying both laterals simultaneously; there is no separate brake control. The basic requirement is that the driver needs two hands available for steering. Gear changes required the driver’s right hand, so only the left was available for steering during shifting.

Human factors design of the driver’s controls in the Sherman was subjugated to the requirement of rapid producibility and ease of maintenance. The driver’s vision was limited to a non-rotating vision block. The magneto switches were often accidentally switched off by the driver’s left knee when he operated the clutch pedal. This resulted in the V-8 engine operating on only one bank of cylinders until the error was discovered. The discovery was often made in the middle of a turn, when the engine could not provide sufficient power to complete the turn. Other than a seat height adjustment, there was no other provision for drivers of varying heights. Drivers often taped wooden blocks to the clutch and accelerator pedals to adjust to length of their legs. The vertical stroke of the clutch pedal required considerable effort. Lighter drivers had to put almost all their body weight on the clutch (a similar action to kick-starting a motorcycle), leaving little support for the rest of their weight, except on the right leg, which was controlling the accelerator. The transmission was non-synchonized, so gear changes required two cycles of weight-shifting and pedal actuation for each shift.

Driver interaction with lateral controls is somewhat intuitive; he merely pulls back on a lever on the side of the vehicle he wishes to slow down. For vehicles with limited power, this has the disadvantage of taking power from the engine only to dissipate it as heat in the brake on the inside track. A better way of doing this is to control the differential in such a way as to allow power absorbed from the slower-turning inside track to be regenerated through the differential to the outside track.

Russian tracked vehicles have traditionally had a compromise system for their laterals in which the first stage of the pull on the lateral merely disengages power from the inside track, allowing full engine power to go the outside track. A continued pull on the lateral brakes the inside track. This scheme presents an exciting scenario for a driver who is driving such a vehicle downhill, using engine compression to assist in braking. In this case, if the driver wants to turn right, he would naturally pull the right lateral. However, this action disengages the right track, while continuing to apply engine braking to the left track. The final result is that the vehicle turns left in response to a pull on the right lateral, and then swerves to the right if the driver continues to pull. The consequences of such control reversals have obvious consequences in limited quarters.

Requiring both the driver's hands for the laterals implies significant tradeoffs for manually-shifted vehicles. The driver can either steer with both hands or manipulate the shift linkage, but not both simultaneously. This shortcoming has been somewhat ameliorated by the advent of automatic transmissions, but lateral steering control has rapidly lost favor in military vehicles.

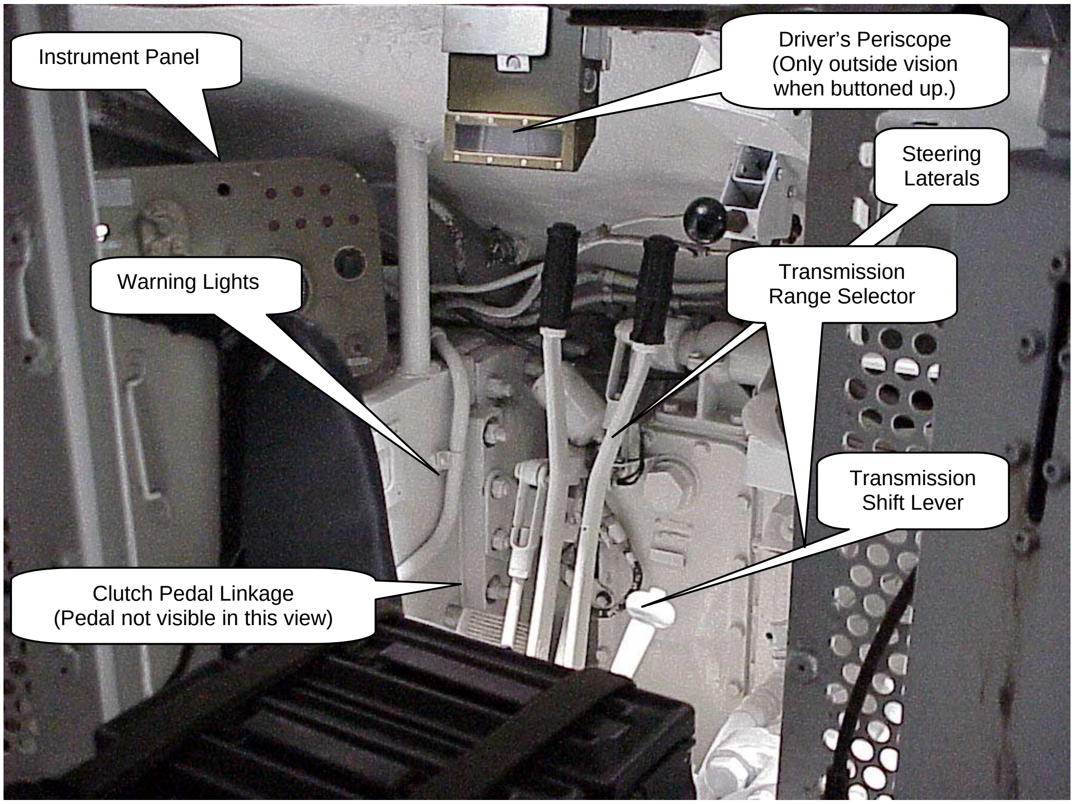

Fig. III.1 - Driver's steering laterals in Sherman Tank

Laterals have a final shortcoming in that they leave the driver with no way to brace himself against pitch oscillations, and braking, except with handles that are also the steering controls. If the driver is thrown forward by an unexpected pitch oscillation, the forward motion of his body leaves him no way to continue to apply braking force to one or both laterals.

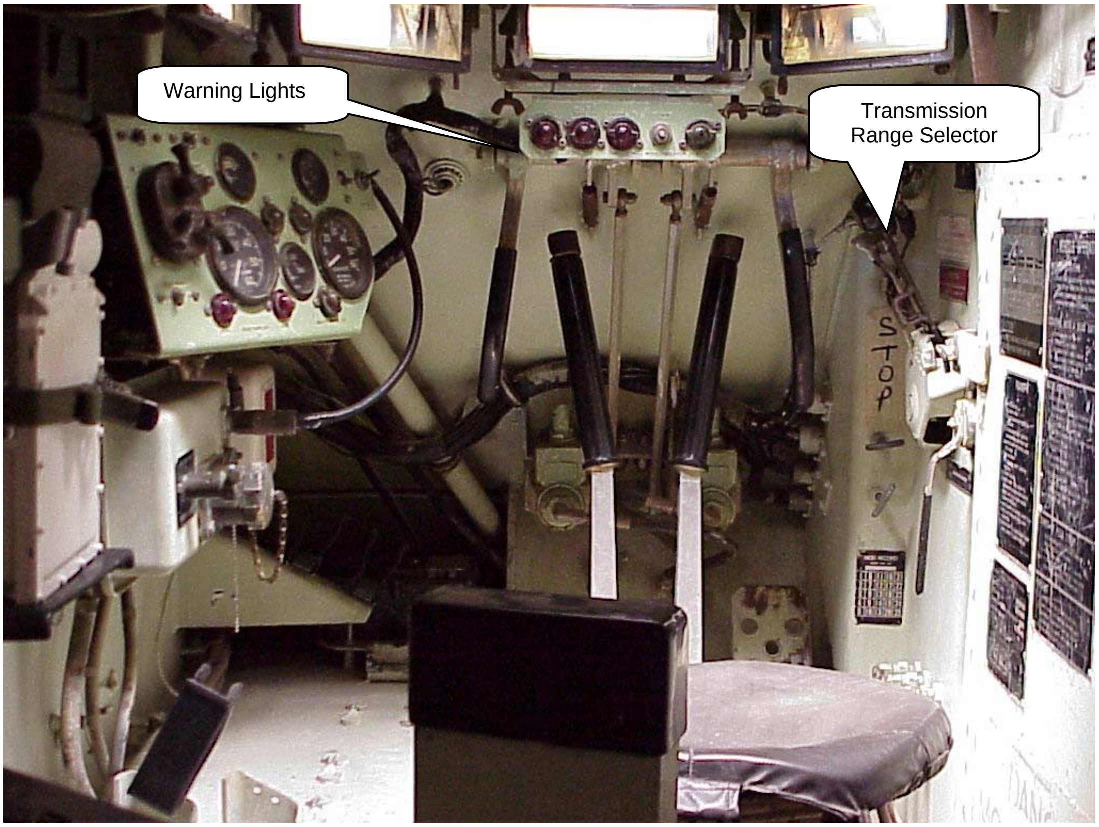

Fig III.2 - In the US M113, the manual transmission shifter has been replaced by an automatic transmission range selector, somewhat easing driver workload. Additionally, warning lights have been added in front of the driver to call his attention to anomalous readings on the instrument panel. Driver vision is improved by multiple periscopic vision blocks.

III.1.2 Steering Wheels and Yokes – This most obvious of steering devices is almost universal among wheeled vehicles, and has also seen considerable use in tracked vehicles, especially since the advent of automatic transmissions. Figure III.3 provides one example of this for a Russian wheeled APC. In combat vehicles, the steering wheel may take the form of an interrupted arc or an aircraft-style yoke instead of a full circle, as demonstrated by the steering yoke of the US M578 in Figure III.4., and III.5 and the elliptical yoke in the US. M88, (Figure III.6). The intent of the modified shape is to provide more legroom for ingress and egress from the cramped driver's compartment. Steering wheels have the advantage of allowing one hand to be free to manipulate the transmission or other controls in the driver's compartment. The wheel also has the advantage of providing a way for the driver to brace his body without providing control inputs.

III.1.3 T-Bar – The T-bar is an evolution of the steering wheel, but is actually more analogous to bicycle or motorcycle handlebars. Early T-bars (starting in the 1950's with the M48 and M60 tanks) provided steering only, with throttle and brakes still controlled by the driver's feet, and the transmission controlled by a hand lever. More modern systems, exemplified by the Abrams tank, have implemented the throttle control as a twist grip on the handlebars, and put the transmission selector in a quadrant between the handlebars, where it can be controlled by either thumb. In the Abrams, braking is still actuated by a foot

Fig III.3 Driver’s station, showing the steering wheel used for directional control of this Russian wheeled APC.

Fig III.4 - US M578 Driver’s station, showing the steering yoke. The yoke used in this vehicle is actually an abbreviated steering wheel, which pivots about the roll axis. Unlike wheeled vehicles, in which several turns of the wheel may be needed for precise steering control, modern tracked vehicles are steered by differentially controlling their sprocket output shafts. Therefore, only limited rotation of the control device is needed. Elimination of the rim of the wheel allows more driver legroom, and eliminates obscuration of the instrument panel.

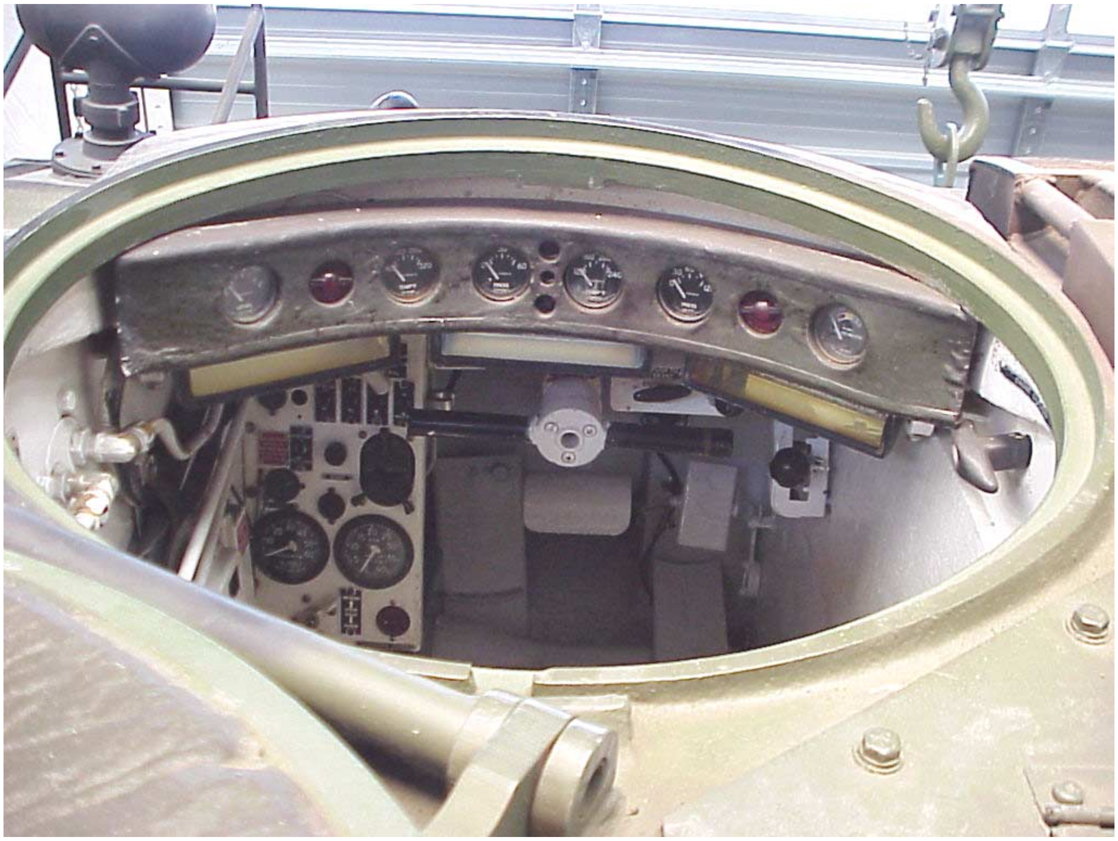

Fig III.5 - Another view of the M578 driver's station. Note supplementary instrument panel containing gauges and warning lights. The supplementary panel could be mounted outside the hatch ring, for better visibility in bright daylight conditions.

Fig III.6 - Driver's station in a US M88 recovery vehicle. The elliptical wheel has its axis offset to provide additonal kneeroom for the driver. The operator frequently stands up in this vehicle to judge clearance, and needs to be able to reach the wheel from a standing position.

pedal, but there is no reason why a control system could not also route braking controls to the T-bar, leaving the driver's feet free for body bracing. Figure III.7 provides another example of a T-bar directional control system in the CCVL.

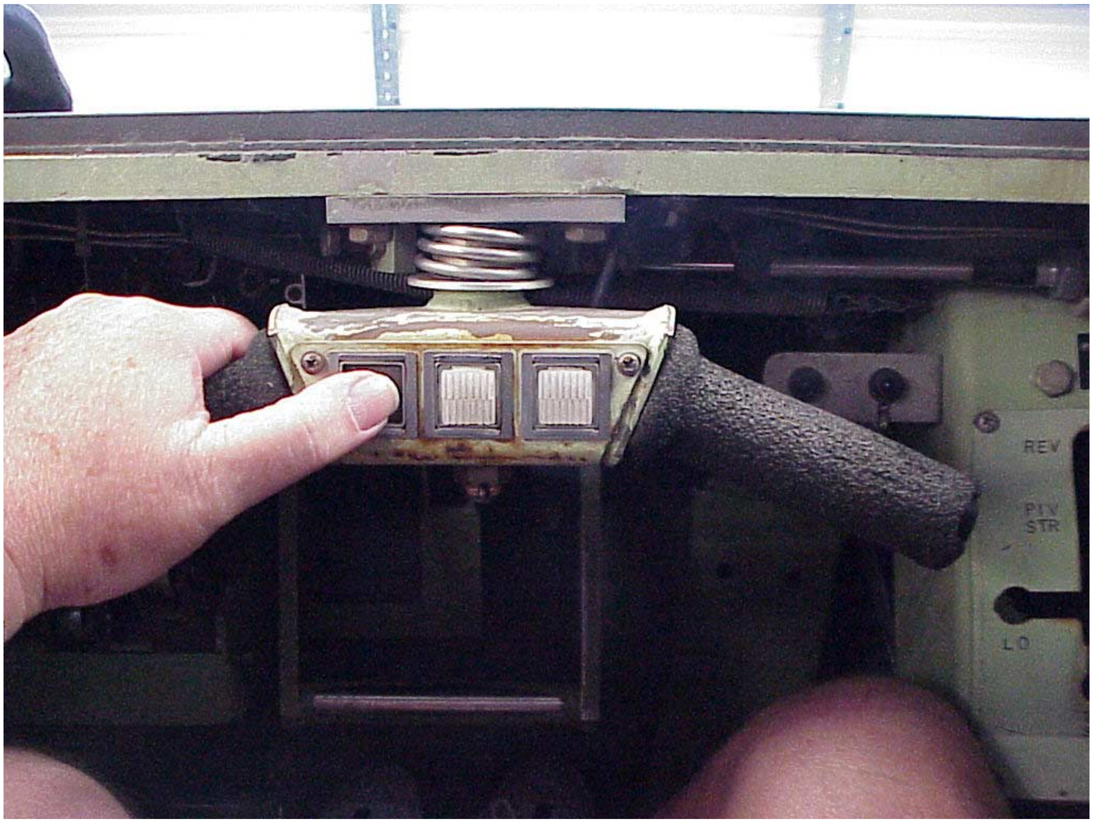

Fig III.7 - Driver's station of a CCVL. Note the T-bar directional control at center, and the transmission range controller at right. The Abrams tank is similar, except that the accelerator is replaced by a motorcyle-style twist grip on the T-bar, and the transmission control is a thumb control on the T-bar pivot. Unlike the yoke, in which steering is affected by rotating the yoke around a horizontal axis, the T-bar is steered by pushing and pulling the handles to rotate the control about its vertical axis.

III.1.4 Joystick – Joystick steering would seem to be a natural evolutionary step in vehicle control, especially for a population accustomed to computerized controls. However, the joystick is a devolutionary step for driver controls, reverting back to the disadvantages of laterals. It provides no body bracing for the driver, and offers few new advantages. Analogies to sidearm controllers for fighter planes are not applicable, because the land vehicle does not pull any sustained g's, which give the sidearm joystick its advantage for aircraft capable of generating high radial accelerations. A contributing factor to the failure of the analogy is that land vehicles do not perform any maneuvers requiring coordinated use of two or more controls.

The US M46 tank had joystick steering in the early 1950's (and M-47 as shown in Figure III.8). A mechanical linkage to a sidearm controller on the driver's right side provided left-right control by tipping the joystick from side to side, and gear shifting by pushing the joystick forward or back. An additional novelty of this system was that the bow gunner, who was seated in the right glacis beside the driver, was provided with a duplicate stick through which he could control the vehicle with his left hand. This gave the driver a respite on long road marches. However, the joystick controller has not been attempted again on either wheeled or tracked military vehicles.

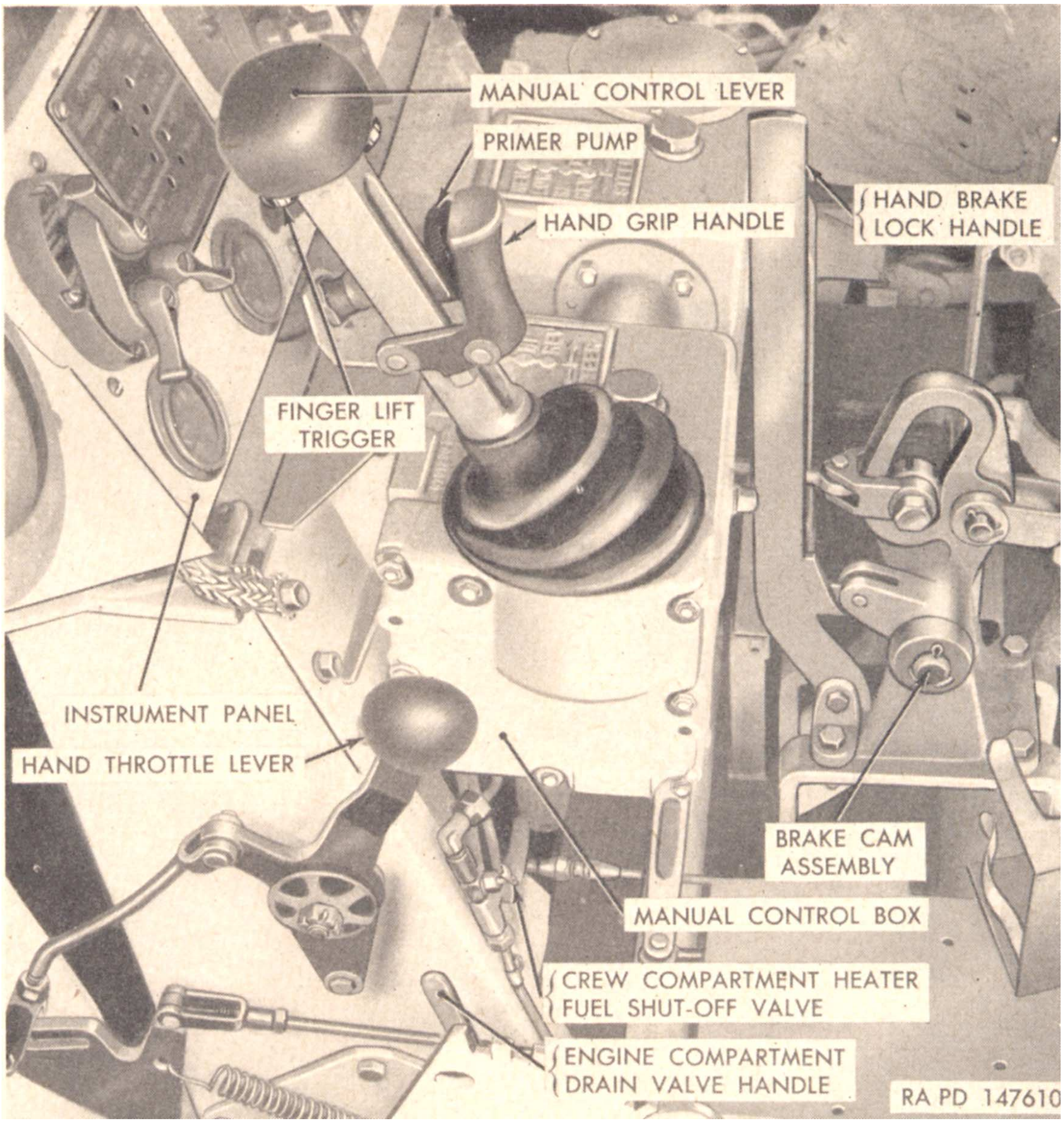

Fig III.8 - Joystick steering control on a US M47 tank from the early 1950's. This was an entirely mechanical linkage, which steered the vehicle with left-right motion and controlled the transmission with forward-backward motion. This is the view from the driver's seat in the left glacis. (Front of the vehicle is toward the left in this view.) The bow gunner of the earlier M46 sat in the right glacis, and was also provided with a steering control. The shared instrument panel sat between the two.

III.2 Loader

Major calibre weapons (i.e., other than belt- or magazine-fed automatic weapons) require some means of supplying ammunition to the breech. If a human loader is part of the crew, his interaction with control systems is usually limited to switches necessary to safe the gun, Figure III.9. However, if an automated loader is employed, it must incorporate several functions which may not at first be obvious:

- Select and load a round to be fired
- Unload an unfired round and return it to the magazine
- Eject the spent casing of a fired round
- Unload a misfire and eject the unfired round overboard
- Unload unfired rounds from the magazine to be taken off the vehicle
- Upload the magazine from rounds passed from the crew
- Maintain an inventory for purposes of requesting replenishment
- Accept non-ready rounds from on-board storage into ready racks

These functions are challenging enough for a weapon firing fixed cartridges, but are even more so for artillery or mortars with variable propelling charges and adjustable fuzes.

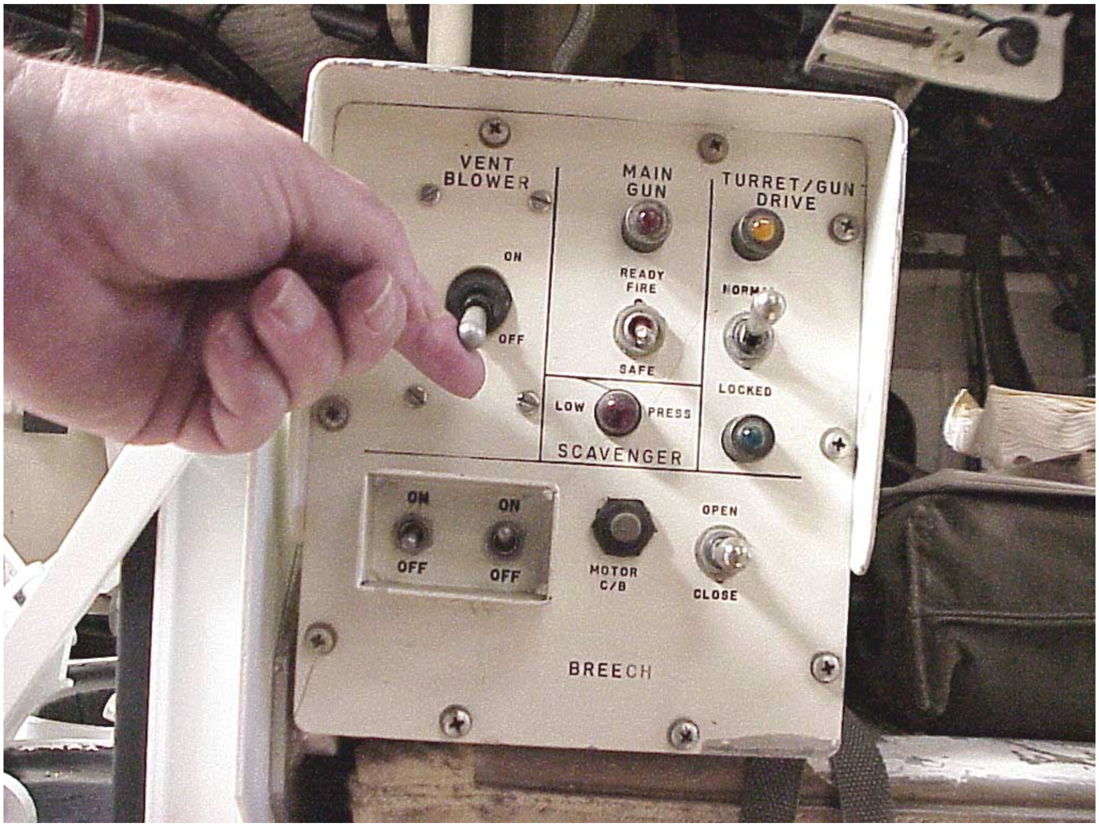

Fig III.9 - M60A2 Loader’s control panel. Note large, widely spaced controls suitable for use with gloves and under low light conditions.

III.3 Commander and Gunner

The commander and gunner are often furnished with redundant weapon controls, so discussion of their roles is combined in this section. These are the crewmembers most heavily involved in maintaining situational awareness. In contrast to the loader and driver, whose attention is focused inside the vehicle or its near vicinity, the attention of the commander and gunner is directed toward tactically significant terrain, frequently at ranges beyond limits of the naked eye. The commander station in the French LeClerc tank is shown in Figures III.10 and III.11.

Target acquisition equipment may include monitors and binoculars or handheld vision aids. The main fire control of modern combat vehicles usually includes image intensifiers and/or thermal sights. Because of the ground clutter problem, radar is not commonly fitted on the current generation of vehicles, but advances in millimeter wave devices are nearing maturity, and radar will likely be included in the next generation of vehicles.

Controls in land vehicles must be operable by a crewmember wearing gloves (either for protection against cold weather or a part of an NBC protective ensemble). Therefore, switches and displays requiring fine manual dexterity are avoided. Because the vehicle operates in a high vibration and shock environment (both from transmitted suspension forces and weapon recoil) controls must be equipped with positive detents, and must have higher actuating forces than would be acceptable in a more benign environment. Because they must be readable while the vehicle is moving, small text legends and symbols are also avoided.

Fig III.10 - Commander’s station in a French LeClerc tank

Head-up displays and voice-activated controls, although common in aircraft, have not been successfully adapted to land combat vehicles. Head-up displays are difficult to implement because the crew spends considerable time using the naked eyes to observe the terrain around them. Unlike an aircraft crewman, who spends the entire mission seated in essentially the same position, land vehicle crewmen move around more, making head-up displays less useful. Voice-activated controls have been tried, but none have been successful to date. The aural environment in and around the vehicle, both from powerplant and from weapon firing, poses a considerable background noise. Also, crew stations may be occupied by alternate crewmembers; the disastrous consequences of having a gunner assume the role of his injured tank commander, and being unable to fire the weapons because his voice was not recognized by a speech-activated fire control system are obvious.

In contrast to air and sea systems, where the relationship of targets to terrain features is of less importance, a major task of the land system sensors is to correlate target signatures to terrain that the crew can see. Multi-sensor integration is being addressed in systems now under development, but is by no means a solved problem. On one hand, the most immediate need the crew has is to superimpose symbology over the perspective view offered by their sights and target acquisition instruments. On the other hand, there is also a need to overlay target information received from external sources. These targets may be not in current line of sight (because of distance or intervening terrain features), and are hence better represented on a Plan Position Indicator (PPI), like the familiar radar screen. The PPI is preferably correlated to a map, and should show identification of the target (IFF information) as well as course and speed. This requires tremendous electronic bandwidth, especially if meaningful update rates are to be maintained. It must also be borne in mind that each platform is a potential source of such target information, as well as a recipient of it, so data processing capacity and throughput rates become even more critical.

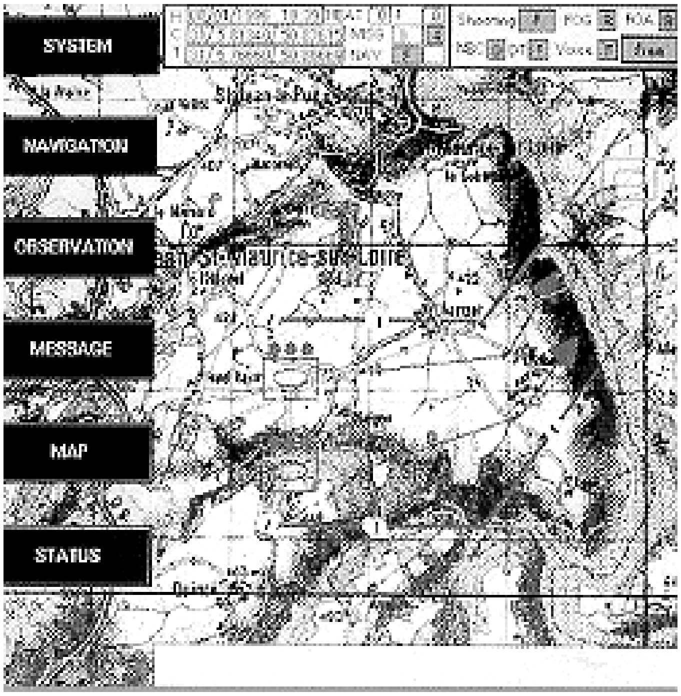

Fig III.11 - Map display at Commander’s station in the French LeClerc. Virtually all modern combat vehicles are equipped with similar systems, or will be in the near future. This display screen takes advantage of the inherent versatility of digital display devices to build “glass cockpits” in which limited display areas can be used to display almost any kind of textual or graphic information.

A major human factors concern in sophisticated target acquisition and situational awareness systems is information overload, especially for crewmen who have insufficient sleep — land combat vehicles virtually never have rotating crews. Design of controls must be simple enough for a fatigued and stressed crewman to operate with ease

III.3.1 Commander and Gunner Station Layout

On vehicles with turrets, the commander and gunner have traditionally been located in the turret. This layout affords them the highest vantage point on the vehicle, as well as the opportunity to maintain situational awareness by remaining orientated in the direction of fire of the vehicle. Examples of various elements of these stations are provided in Figures III.12 – 16.

There is very little standardization among countries, and even vehicles from the same country have inconsistent design practices.

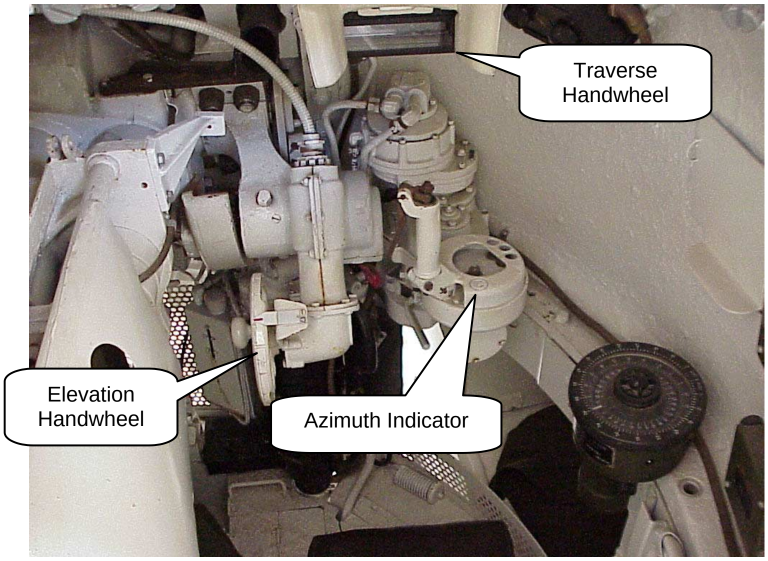

Fig III.12 - Gunner’s station on a US Sherman tank from WWII. Traverse is controlled by rotation about the yaw axis, and elevation is controlled by the handwheel in the pitch axis. Although primary gunlaying controls are manual, the gun has a single-axis elevation stabilizer. Power traverse allows rapid slewing to acquire targets, but manual traverse was preferred for target tracking. An azimuth indicator, accurate to 1 mil was fitted for use during periods of limited visibility, and for the secondary indirect-fire mission. Modern tanks have provision for night vision, and high velocity guns have obviated the artillery mission, so azimuth indicators are no longer fitted.

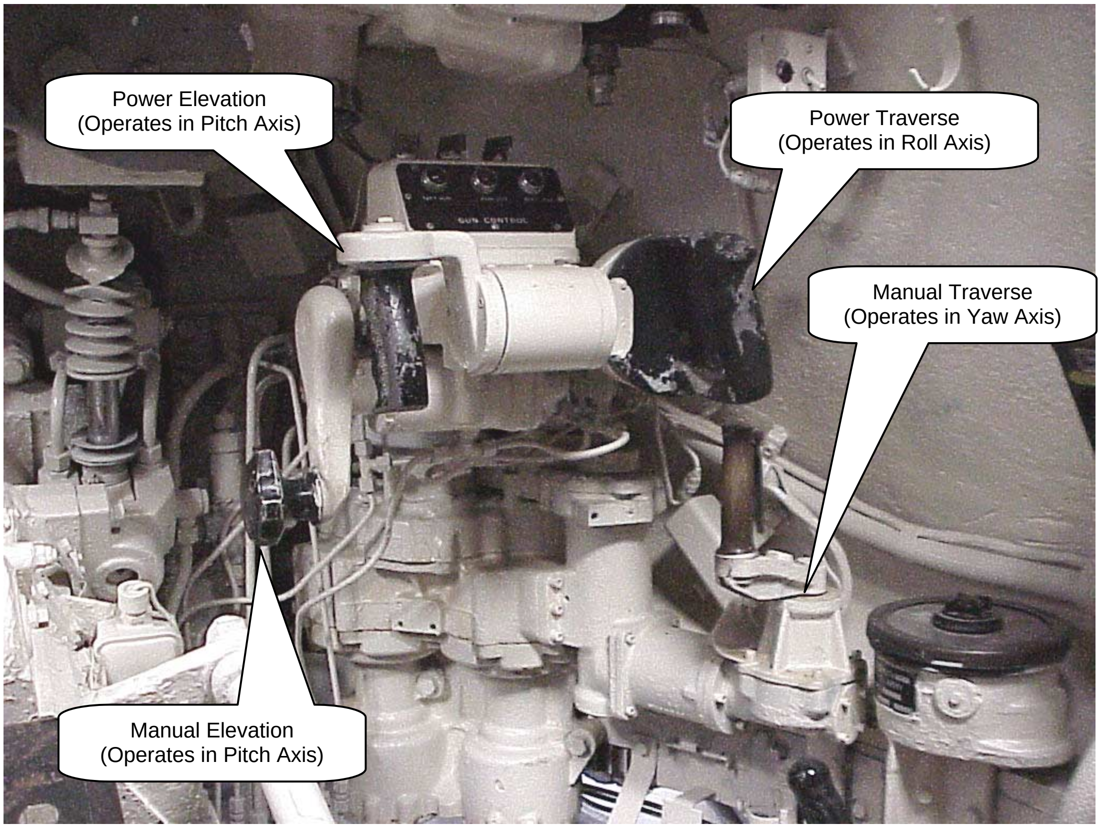

Fig III.13 - Gunner's station in a US M47 tank. Power traverse is available through a pistol grip which rotates about the roll axis, as does the manual elevation control. Power elevation is available through a separate control that moves in pitch, while the manual traverse control rotates in yaw.

Fig III.14 - The M47 commander's turret elevation control moves in pitch, but rotates in yaw to control traverse.

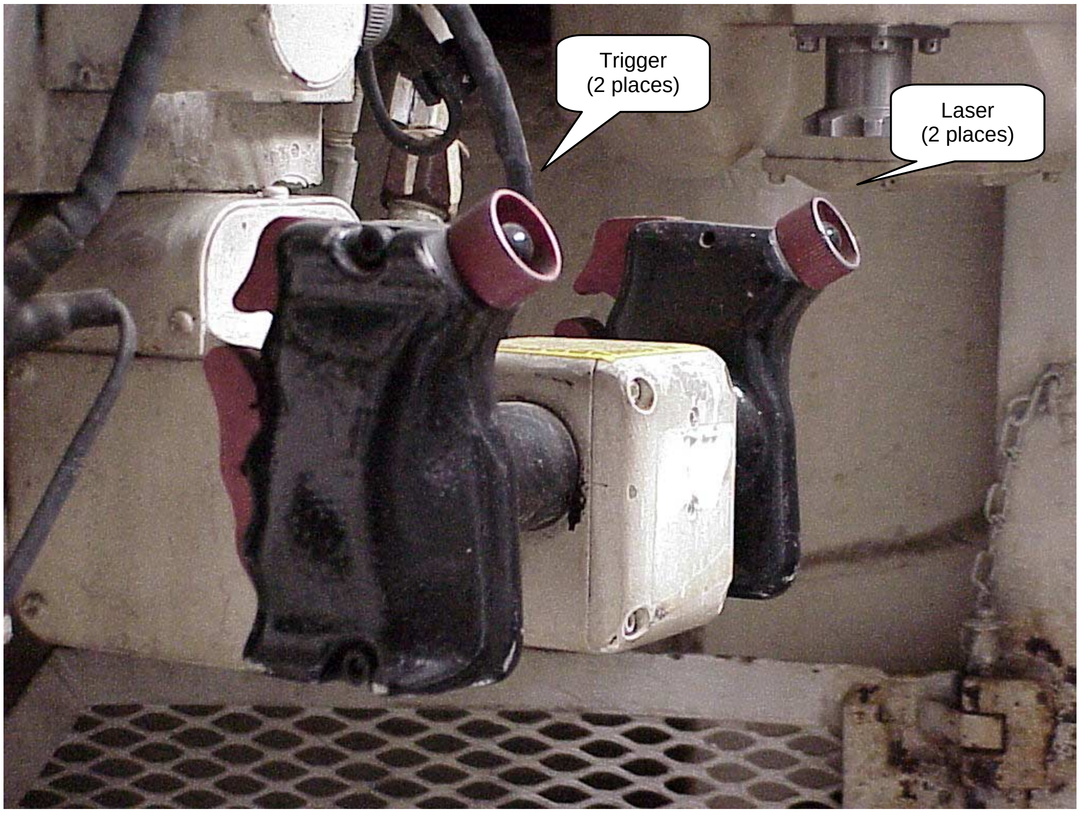

Fig III.15 - Gunner's primary controls on a US M60A2. This layout has now become standard on US vehicles. The entire control yoke moves in roll to control turret traverse and in pitch to control gun elevation. Thumb buttons activate laser rangefinder, the "trigger finger" switches control weapon firing, and switches under the other fingers energize the entire control. This last feature is necessary to prevent turret drives from being activated by an inadvertent bump. Switches on each side are redundant, but only one side being required to activate the control.

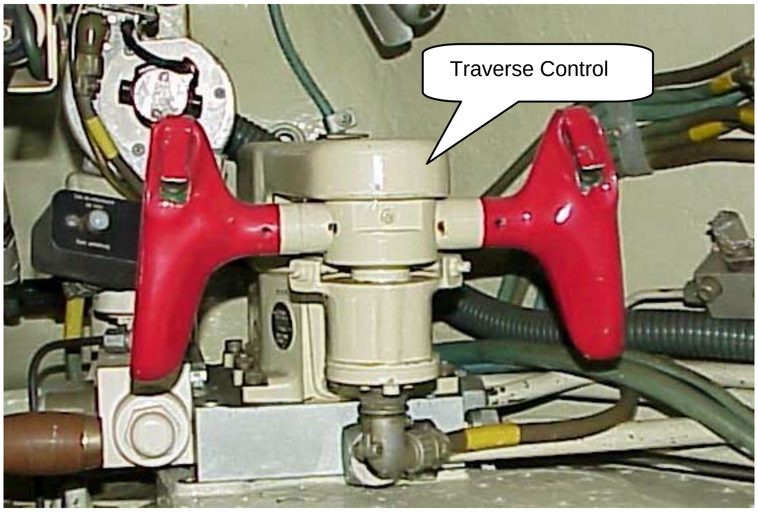

Fig III.16 - Gunner's control on this Swiss Pz61 rotates in yaw to control traverse.

A few exceptions to the traditional layout have been attempted in the past, and are worthy of mention here. The US M60A2 tank had a powered commander's cupola (Figure III.17, III.18), which was independently rotatable from the turret and was independently stabilized in elevation and traverse. The cupola contained a completely redundant set of gunner's controls that allowed the commander to fire the main weapon. The concept of this vehicle was that the commander could be maintaining situational awareness, to include selecting the next target, while the gunner serviced the current target. The vehicle was equipped with image intensifiers at both stations, and offered unprecedented observation, target acquisition, and target engagement. In practice, this setup was less than successful, especially in limited visibility when terrain references were limited. When the vehicle was moving, a commander was subject to conflicting motion cues from hull motion, upon which was superimposed turret motion, upon which was superimposed the motion of his cupola. The resulting tendency toward disorientation and motion sickness caused the crews to keep the cupolas aligned with the turret when on the move, and only independently trained when the tank was stationary. The independent viewers fitted to M1A2 Abrams and M2A3 Bradleys present this same situation, although neither of these vehicles has been used in maneuvering combat, so the problem has not been widely addressed.

Fig III.17 - A US M60A2 tank. The large commander's cupola was independently stabilized in elevation and traverse. Upon acquiring a target, the commander could engage it with the .50-caliber machinegun, or could take control of the turret and "auto-align" the main weapon to the target currently in the cupola crosshairs. The commander's cupola controls could also be used to fire the primary armament in the event the tank was operated with a three-man crew, without the gunner. In practice, the workload on the combined commander/gunner was significantly increased, and this practice was not seen as a favorable indicator of desirability of a reduced crew.

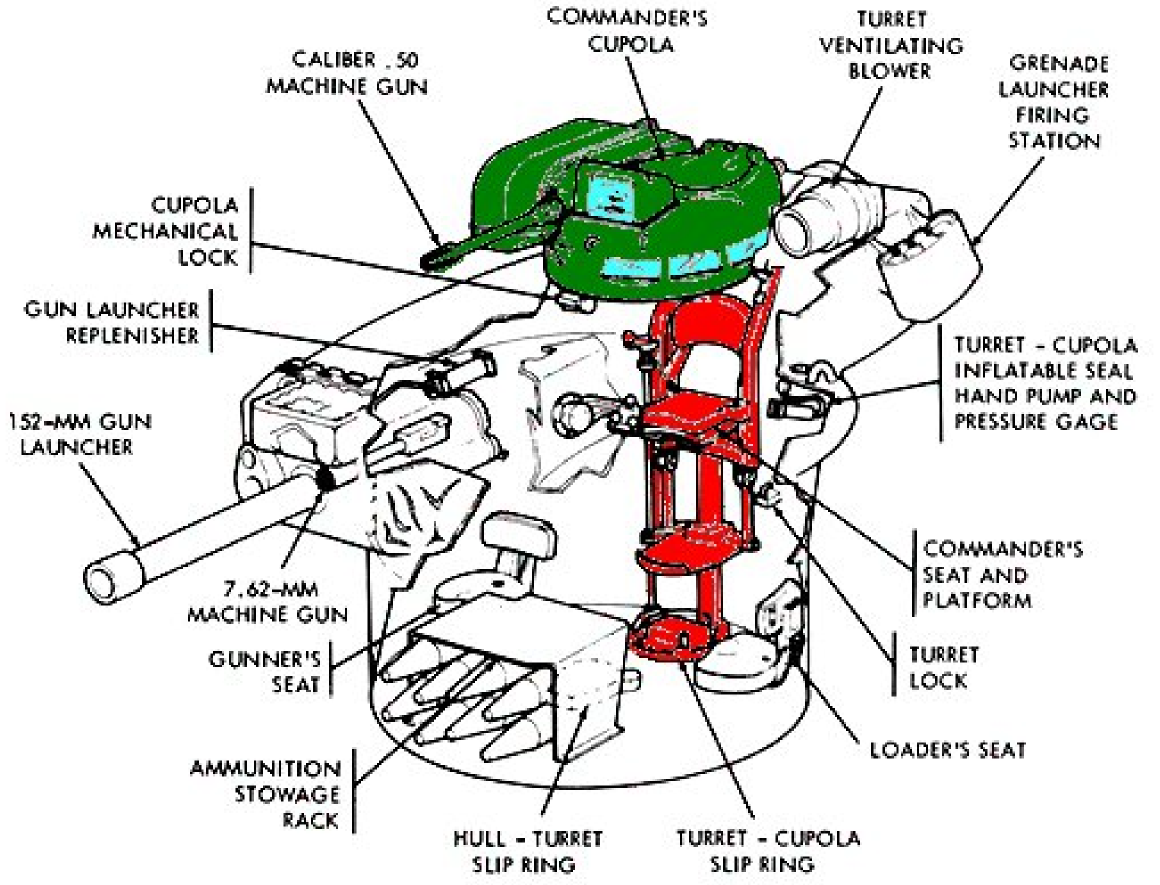

Fig III.18 - Turret arrangement of the M60A2 tank. The cupola (in green) was independently stabilized in two axes. The commander's seat (in red) had its own slipring, and rotated with the cupola. In practice, commanders had difficulty in maintaining orientation and situational awareness, particularly during periods of limited visibility when there were few intuitive external clues. Consequently, the system was usually kept aligned with the main turret, except in stationary situations. The vehicle was controlled by an analog computer, and required constant attention to its nulling controls to maintain alignment and prevent drift, primarily in response to temperature variations in the equipment.

As previously discussed in the section on driver's controls, the Swedish Stridsvagn 103 had a three-man crew, which included a commander, radio operator/rear driver, and a gunner/driver. Although this tank was designed to a unique Swedish requirement, the integration of multiple crew duties into one station provides an example of the challenges to be faced in future systems with reduced crews and consequent control integration (Figures III.19, III.20)

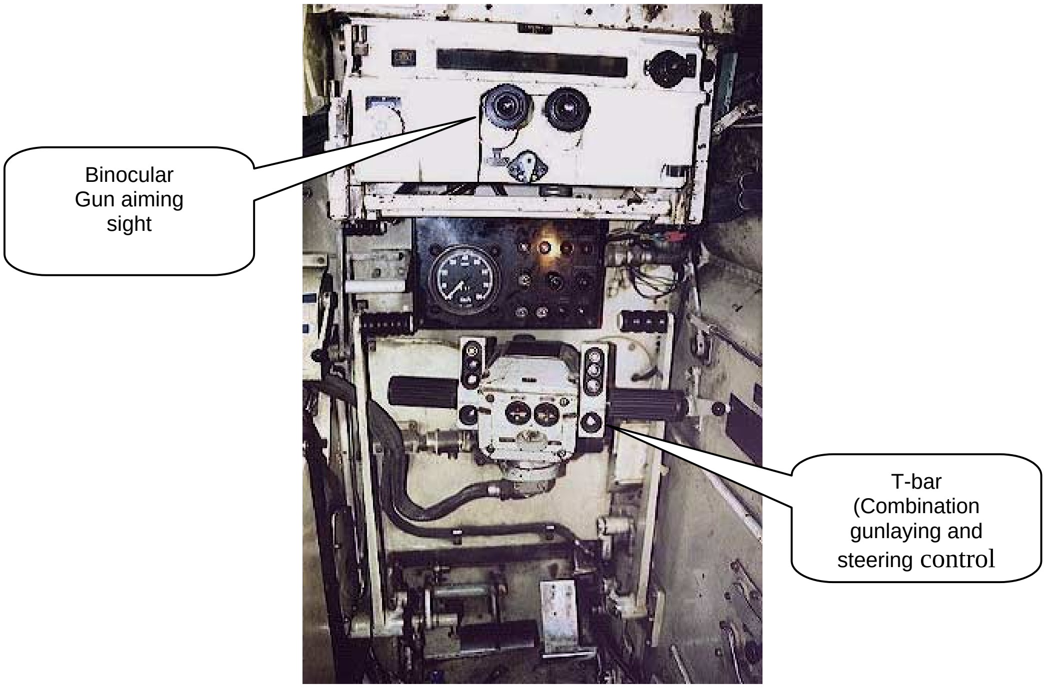

Fig III.19 - Swedish S-tank driver-gunner's station. The T-bar is near center of the photo, with driver's instruments (black panel) immediately above. The binocular sight eyepiece and a unity-power vision window are at top.

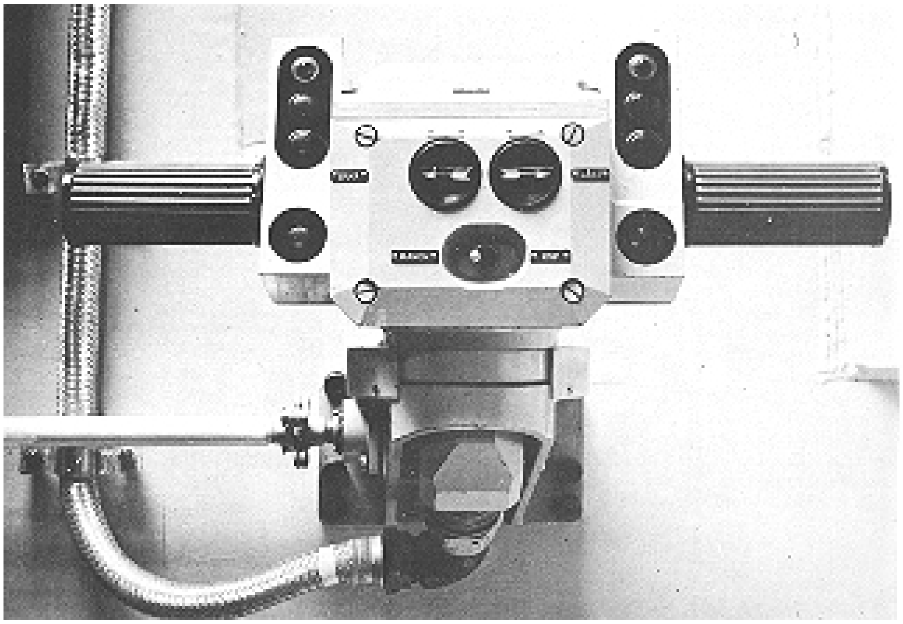

Fig III.20 - Combination steering T-bar and gun-laying control of the S-tank. Gun elevation axis was controlled by twisting the grips to alter the first and last suspension units to change the pitch attitude of the entire vehicle. Traverse was accomplished by rotating the yoke about the yaw axis to counter-rotate the tracks using engine power. The rear-facing radio operator had a less elaborate control, because there was no provision for him to sight or fire the gun.

Various experiments have also been carried out, both in the US and abroad that place the commander and gunner functions in fixed, non-rotating positions in the hull. (This layout is the exact converse of the MBT-70, which had all crewmembers in the turret.) The unmanned turret is an attractive layout from an engineering standpoint, because it simplifies the turret slipring, reduces space requirements inside the turret, lowers the silhouette of the vehicle, and potentially places crewmen in better-protected areas of the vehicle. However, the consequences of having the crew maintain situational awareness while observing or firing weapons in directions other than that in which they are traveling re-raises issues of motion sickness and disorientation which have presented problems in other vehicles.

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APPENDIX IV

Glossary

ACV	Air Cushion Vehicle
AIP	Air-Independent Power
APC	Armored Personnel Carrier
AUV	Airborne Unmanned Vehicle; Autonomous Underwater Vehicle
CCP	Cyclic/Collective Pitch (rotor)
CFD	Computational Fluid Dynamics
CG	Cruiser, Guided missile
CODOG	Combined Gas (turbine) Or Diesel
CPP	Controlled-Pitch Propeller
CV	(Aircraft) Carrier
CVN	(Aircraft) Carrier, Nuclear
DD	Destroyer
DDD	Deep Diving Depth
DGPS	Differential GPS
FF	Frigate
GPS	Global Positioning System
IMO	International Maritime Organization
INS	Inertial Navigation System
ISO	International Organization for Standardization
LAPES	Low Altitude Parachute Extraction System
LH	Liquid Hydrogen
LR …	Long Range …
LVDT	Linear Voltage Displacement Transducer or Linear Variable Differential Transformer
MAD	Magnetic Anomaly Detection
MBT	Main Battle Tank
MCM	Mine CounterMeasures
MED	Maximum Excursion Depth
MII	Motion-Induced Interruption
MLD	Manoeuvring Limitation Diagram
NATO	North Atlantic Treaty Organization
OFE	Operational Flight Envelope
ORSIS	On and Off Road Systems Interactive Simulation
PD	Periscope Depth
PID	Proportional, Integral, Differential (hence PD, etc.)
PMM	Planar Motion Mechanism
RAO	Response Amplitude Operators
RCS	Reaction Control System
RTO	Research and Technology Organization

RMS	Remote Minehunting System, Ride Motion Simulator, root mean square (in lower case)
RO/RO	Roll On / Roll Off
ROV	Remotely Operated Vehicle
SAE	Society of Automotive Engineers
SAM	Surface-to-Air Missile
SES	Surface Effect Ship
SOLAS	(International Convention on) Safety Of Life At Sea
SP …	Self-Propelled …
SSBN	Ballistic missile Submarine, Nuclear
SSM	Surface-to-Surface Missile
SSN	Attack Submarine, Nuclear
SSK	Attack Submarine, conventional (Killer)
STANAG	Standard – Naval Armaments Group
STOVL	Supersonic Takeoff and Vertical Landing
UAV	Unmanned Airborne (also, Uninhabited Aerial) Vehicle
ULCC	Ultra-Large Crude Carrier
UUV	Unmanned Underwater Vehicle
VLCC	Very Large Crude Carrier
V/STOL	Vertical/Short Takeoff and Landing
VTOL	Vertical Takeoff and Landing
WIG	Wing In Ground-effect vehicle

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System identification
Vehicle dynamics

14. Abstract

This technical report is the culmination of the SCI-053 Task Group – Vehicle Dynamics, System Identification, Control and Handling Qualities. It summarizes the discussions of tank, truck, aircraft, helicopter, ship, submarine and satellite experts held over a three-year period. It addresses the various technical areas identified in the name of the task group, exploring the similarities and differences between the vehicle types and identifying areas where collaboration between experts would be the most valuable. Twenty-three specific technical issues are identified as initial areas with high potential for valuable collaboration. Overall, the report provides the vehicle expert of one environment a sufficient background on the other vehicle environments, so that meaningful discussions towards these technical collaborations can be initiated.

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