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MANNED FLIGHT SIMULATION--CHALLENGE AND RESPONSE

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SUMMARY

Early AGARD papers on manned flight simulation describe the status of an emerging test technique and then offer suggestions of problems that should be solved to advance the technique and predictions of the results that will be obtained by its use Later AGARD literature is examined to determine how these challenges have been met, both in ground-based and in-flight simulation and how AGARD has played an important role in advancing the technique so that it is now an integral part of the aerospace vehicle design process

INTRODUCTION

Even before his first powered flight, Wilbur Wright recognized the problems of integrating the man and the flight vehicle In 1901 he said, "Man already knows how to construct wings or aeroplanes, which, when driven through the air at sufficient speed, will not only sustain the weight of the wings themselves, but also that of the engines and the engineer, as well Men also know how to build engines and screws of sufficient lightness and power to drive these planes at sufficient speed . Inability to balance and steer still confronts students of the flying problem . . When this one feature has been worked out, the age of the flying machine will have arrived, for all other difficulties are of minor importance " (Ref 1)

With difficulty the Wright brothers found how to balance and steer their flying machine, but it still remained a problem to teach others. Starting about 1910, all manner of training simulators were employed to teach others how to fly and how to alter the man's knowledge to fit the machine he operated However, as man attained skill in constructing flight vehicles he found that those machines had to be designed to be compatible with the men who would operate them, that is, the machine had to be made to fit the man. The answer lay in the research and development simulator The development of research and development simulators drew on the early experience gained in training simulators and progressed through a series of steps that can be traced in the publications of AGARD, which played an important role in their development Progression from one step to another depended both on the confidence of pilots and engineers that the information obtained from simulators could be depended on for use in vehicle design and on technical and scientific advances that made it possible to build simulators that presented the pilot with a better simulation of flight cues

THE CHALLENGE

"The science of engineering is that of predicting the performance of machines If man controls the machine we have to study the complete system with the human operator as an integral part To improve performance of the system, the machine has to be modified to suit the human controller and the controller has to be modified to suit the machine If man's limits are reached, the designer will replace him with automation However, man can discriminate and adapt himself, he is the supreme servomechanism The human pilot is still the only controller who can cope with emergencies, will resist detection by jamming and decoys It is difficult to conceive that he will not continue to control aircraft for years to come In order to utilize his skill efficiently we will have to learn to understand his faculties " This was W J G Pinsker's opening statement in his 1956 presentation of the first AGARD report on manned flight simulation (Ref 2) It is a succinct statement of the system design problems for which flight simulation has proved to be a most successful and economic tool In his concluding remarks, Pinsker set goals for the simulator designer and user "The pilot controls the aircraft primarily by visual reference to the ground or to instruments and in response to the physical sensation of movement A successful flight simulator will probably have to produce a convincing analogue of both " His prediction of the future is conservative "It is not inconceivable that in the not very distant future, an aircraft control system can be designed and properly matched to the aircraft by studying it in a flight simulator "

A continuing objective of aircraft designers and builders is to develop aircraft and their systems and to bring them to operational status as expeditiously and economically as possible Simulation is, of course, only one of the tools used in attaining this objective There have been a number of steps in the progress of research and development simulators, steps that have been determined by aircraft development goals and made possible by scientific and technological advancements

RUDIMENTARY SIMULATORS

The availability of analog computing techniques in about 1945 was critical to the development of the simulator for aircraft research and development purposes With the exception of training-simulator developers, who were already using the technique, it is likely that no aeronautical organization bought its

*Retired

first computing apparatus for the purpose of using it in the assembly of a man-in-the-loop simulator Instead it was bought to solve the organization's most intractable problems, the ones that could be formulated well but were difficult or time-consuming to solve because they contained many differential equations and nonlinear functions The speed with which these computing techniques could solve problems, particularly optimization problems, attracted new users to the computing apparatus, and soon the techniques began to be used on real-time problems. The new users wheeled this early computing apparatus up to aircraft test stands and to airplanes on the ground in efforts to resolve some of their automatic system problems, including the development of the newly emerging variable-stability aircraft The apparatus was even applied to that most intractable of all problems, control systems involving man Rudimentary research and development simulators apparently emerged at about the same time at a number of different locations They comprised little more than (1) the computing apparatus connected to a control device, (2) at least one simulated instrument, probably a voltmeter or a horizon line on a cathode-ray tube, and (3) the all-important man

DOMINANT-CUE SIMULATORS

Only limited results could be obtained with those first simulators, but they were good enough to encourage the research and development workers to proceed to the dominant-cue simulator--a simulator that presents to the pilot a good simulation of the cue that dominates his perception and affects his response in the task to be studied Important factors in the decision to proceed to this class of simulator were the existence of a problem, confidence that simulators could be used in aircraft research and development, and the availability of the technology necessary to build such a simulator The problem was man and the inability to define precisely enough his action as a controller, to understand his faculties The most important of the new technology was what was called the general-purpose analog computer, designated in Fig 1 as the electromechanical computer, since it still contained mechanical elements However, this new class of computers used chopper-stabilized amplifiers, which provided a great increase in the consistency of results Servo-set potentiometers and interchangeable patch boards provided the ability to use the same computer on more than one problem at different times of the day, and for the programming connections to be made without interfering with other users Thus, the computer was available to several users and no longer had to be part of the simulator or other hardware involved in a real-time problem

The characteristics of a particular dominant-cue simulator were dependent on the particular problem set it was designed to solve, and its design was likely to have drawn heavily on precedents in techniques and equipment of already-successful training simulators For the simulator described in Pinsker's first AGARD paper, the man-in-the-loop problem was tracking, and the dominant cue was visual For other investigators, their man-in-the-loop problems were best solved by providing the inertial cues of motion

Papers describing research results obtained from these dominant-cue simulators appear in the AGARD Flight Mechanics Panel literature of about 1960 to 1963 Examples of the reporting of these kinds of results on generic problems include the papers of Cooper (Ref 3) and Barnes (Ref 4) on takeoff and landing research (Cooper's 1958 paper, presented before the same Panel, described the same sort of work done by flight research and described by Drinkwater et al in Ref 5) By 1961 the Flight Mechanics Panel was able to devote an entire session of its symposium to the emerging art of simulation In addition to a paper on mathematical modeling by Brown and Paddison (Ref 6), Westbrook spoke on simulation in modern aircraft design (Ref 7), and indicated that Pinsker's goal of designing specific aircraft systems had been met Rathert et al described the use of piloted simulators in general research (Ref 8) Since the introduction of simple variable-stability aircraft in the late 1940s, the capabilities of those vehicles had been increased to the point at which they could be called in-flight simulators, and Kidd et al could title their paper, "In-Flight Simulation--Theory and Application " (Ref 9)

Critical to the acceptance of this class of dominant-cue simulators by pilots and engineers was the demonstration of their usefulness in studies of essentially unprecedented vehicles and in studies of missions in environments that at the time could only be simulated and not experienced In this 1960-1963 period, A'Harrah reported on his investigations of the low-altitude, high-speed handling and riding qualities of aircraft (Ref 10), Neil Armstrong, the first man on the Moon, and Euclid Halleman described the use of in-flight simulation in the space program (Ref 11) Results of the kind reported in those papers were critically important to the advancement of the simulation Simulation was used for such studies because there was no alternative way to do the work The use of a particular dominant-cue simulator might be largely limited to a particular flight segment in which there was an easily chosen dominant cue that the simulator could accurately reproduce, but both engineers and pilots could place enough confidence in the results to move into the next class of simulators--multiple-cue simulators Curiously, results obtained in simulations of unprecedented vehicles were accepted for use in the design of those vehicles before such results were accepted for use in the design of vehicles for which many design precedents existed

MULTIPLE-CUE SIMULATORS

Acceptance of the dominant-cue simulators elicited confidence in the transition to multiple-cue simulators, which provided a wider range of cueing devices That this transition was occurring can be seen in the contents of the 1964 meeting of the Flight Mechanics Panel, the first FMP meeting devoted entirely to manned flight simulation (Ref 12) Papers presented at that meeting described the results of studies carried out in dominant-cue simulators, and all of the authors spoke of the constraints imposed upon their results by the limitations of the simulators used. The limitations derived both from the failure of the simulators to reproduce faithfully some of the cues and from the author's incomplete understanding of the effect of the total absence of others The paper in Ref 12 simulator hardware described lies on both sides of a dividing line between dominant-cue simulators and multiple-cue simulators And the author of the paper on computing facilities could only foresee the application of all-electronic digital computers in a research and development setting, even though such computers were already being used in training simulators

In his introduction to that 1964 FMP symposium, Harper (Ref. 12) summarized the simulator and experimental design problems that had to be met, if simulation techniques were to be developed in a straightforward manner

1 Providing an adequate and representative environment to the simulator pilot--the simulator hardware problem

2 Providing a sufficiently complete and accurate computing facility and at the same time constraining it to practical limits--the simulator computer problem

3 Choosing the adequacy of the required simulator equipment when there was little directly-applicable quantitative knowledge of human perception on which to base a choice--the problem of scarcity of knowledge of human perception

The response to these challenges will be considered below

The multiple-cue simulator, the problems that directed its development, and the technology that allowed it to be developed are shown in Fig 1. The confidence that pilots and engineers had come to place in the results obtained with earlier simulators confirmed that the technique could be used to produce design-useful results Total vehicle design, including the integration of the various on-board and ground-based systems, was the problem that multiple-cue simulators could solve It is interesting to note that the problems involved in total design are, in a sense, less difficult Since simulation worked well on problems for which no alternative testing methods were available, the goal became one of using the technique on problems for which other but more expensive solution methods existed The improved technology of television made possible better out-the-window visual systems Fully electronic digital computing, which had been demonstrated in a training simulator in 1960, had advanced so that it could be usefully applied in research and development simulators. The transition from a dominant-cue simulator to a multiple-cue simulator was sometimes a gradual one--for example, an existing simulator might be modified by adding a better visual system, a platform motion system, or audible-cueing equipment, by generally upgrading the cockpit instrumentation. Sometimes the transition was more drastic--the building of an entirely new simulator

By 1968, in the AGARD Lecture Series on The Aerodynamics of V/STOL Aircraft, Yaggy devoted several thousand words to describing the uses of simulation in V/STOL research, development, and design and asserted that " the degree of sophistication which was begun in the fifties for aircraft simulation was well beyond that which had been accomplished in any previous time period " (Ref 13) Yaggy also discussed the limitations of simulation, but nonetheless called the results "meaningful and gratifying "

That simulation was becoming a mature experimental technique in the late 1960s can be inferred both from the increasing number of AGARD papers on simulation during that period and from the contents of the 1970 AGARD Flight Mechanics Panel Symposium on Simulation (Ref. 14) Previous AGARD papers had described successful results, but simulator users present at that symposium were prepared to be retrospective, to analyze simultaneously the results of a number of simulations, to look for common successes and limitations, to draw conclusions on facility and experimental requirements, to teach, and to learn. The organizers of the conference specifically invited papers on the objectives of simulation, on the mathematical models used, on the motion, visual, and aural cues, on the cockpit environment, on the choice of simulators, and on the design of experiments The presentation of each paper was followed by discussions of other points of view, and those in attendance at the conference were encouraged to share their experiences and opinions on these subjects

Five years later, in 1975, there was solid evidence that the goals of preliminary vehicle design validation and flight-test planning had been reached, aided by the use of multiple-cue simulators The results can be seen in Spitzers's paper on the use of a flight simulator in the design of the YC-14 (Ref. 15), presented at that year's Flight Mechanics Panel Symposium on simulation Spitzer's paper showed that multiple-cue simulators helped him reach his goals of preliminary vehicle design validation and flight-test support, including pilot training. He was careful to point out, however, that although multiple-cue simulators were important to the critical testing involving more than a single mission segment or a single aircraft system, much simpler simulators were also used in the YC-14 design, and they were adequate and economical in many design phases In the preface to the proceedings of that symposium, cochairmen Leondes and Gerlach summarized the symposium round-table discussion in which two of the points that were raised were the same as those brought up by Harper 11 years before in Ref 12 the necessity of improving the cue-producing hardware, particularly the visual, and the necessity of better understanding man's perception and use of cues in a simulator They also underscored the point made by Spitzer that the most cost-effective simulator is not necessarily the most elaborate one.

THE SIMULATORS OF TODAY AND TOMORROW

The beginnings of the transition to the simulators of today and those of tomorrow can be seen in the proceedings of AGARD's 1978 Symposium on Pilot Aircraft Simulation Techniques (Ref 16) A range of simulation topics was covered by the papers presented at that meeting, but this time a larger portion of the proceedings was devoted to finding the elusive answer to the problem of understanding the man and his perception of cues in an aircraft and how such information could be used in simulator design A reading of the conference proceedings shows that problems were arising in relation to flight vehicles that were more difficult to control, particularly in the man-machine interface. The authors of the papers contained in Ref 16 seemed confident that multiple-cue simulators had been successfully applied to the solution of similar problems in the development of earlier aircraft, and they wanted to construct new simulators that would be equally applicable to these newer, less-docile flight vehicles More was known about the man, and more was known about how the advances in technology could be applied to the solution of simulator problems These technological advances had taken place primarily in microelectronics, and they heavily influenced the ability of simulator designers to produce better out-the-window visual systems. This improved understanding of man and of his perception of flight cues allows us to apply the technological advances in an intelligent and economic manner The research and development needs for tomorrow's simulator can be seen emerging in those papers from the 1978 Flight Mechanics Symposium on Simulation

There remain many applications for dominant-cue and multiple-cue simulators, and it is worthwhile to assess the uses and costs, as well as the reliability of the results obtained with the various classes of ground-based simulators. The measure of the complexity of the real-life task (Table 1) includes the range of vehicle types and their systems, the percentage of vehicle mission that can be simulated, and the difficulty of the pilot-operator's task The confidence in the results obtained with the dominant-cue simulator may seem low to some users, and it should be remarked that the range would be higher if one could be certain that omitted cues or cues that were poorly presented were not important to the test conducted Therefore, experimental design is an important factor in the reliability of the results More cues are simulated well in the multiple-cue simulator, but at an increase in operating cost as well as in first cost Confidence in the multiple-cue results is higher, but again at a higher cost. Experimental design and the effectiveness with which the simulator is used, will greatly influence the complexity of the real-life task an experimenter can undertake to simulate In tomorrow's simulators, an increase in all the numbers can be foreseen The ultimate objective is expeditious and economic flight-vehicle development An increase in simulation cost can be justified if simulation decreases the total cost of developing a vehicle

One conclusion that can be drawn from Table 1 is that not all simulations should be conducted on tomorrow's advanced simulators There are many aircraft research and development tasks, many systems problems and generic problems, that still can and should be investigated on dominant-cue or multiple-cue simulators In-flight simulators (Table 1), should be subdivided, to reflect more accurately their use The relatively wide range of values is a result of the fact that some of these simulators are designed primarily for helicopters and others primarily for different types of aircraft

THE ROLE OF AGARD IN SIMULATION

AGARD has played an important role in the development of manned flight simulation It has brought together people from throughout NATO to share and discuss the newest developments in simulation and their uses in aircraft research, development, and design AGARD has played an active role through its working groups, where the requirement that a written report be produced that is acceptable to all members means the facing of issues that an individual might otherwise avoid These AGARD publications include advisory reports on simulator visual systems (Ref 17), on platform motion systems (Ref 18), and on future requirements for airborne simulation (Ref 19)

The foregoing has summarized the work of AGARD's Flight Mechanics Panel, but important contributions to simulation techniques have also been forthcoming from the Aerospace Medical Panel, the Avionics Panel, and the Guidance and Control Panel Even the Propulsion and Energetics Panel has published a paper involving a manned flight simulation Since avionics equipment uses much of the same hardware that is used in simulators, it is natural that new avionics equipment and techniques reported by AGARD include the use of simulation in their development. Similarly, guidance and control uses techniques in common with simulation, so the reports of that symposium more often include man-in-the-loop simulations The symposium held last spring by the Guidance and Control Panel (Ref 20) is of particular interest, since it describes several new helicopter simulators in France, Germany, and the United States The Aerospace Medical Panel has published a large amount of work, both on psychophysiological characteristics of the human and on training-system requirements These include several conference proceedings, as well as such titles as "The Use of Simulators for Training In-Flight and Emergency Procedures" (Ref 21), "Mathematical Models of Human Behavior" (Ref 22), and "Human Factors Topics in Flight Simulation" (Ref 23), an annotated bibliography The advisory report "Fidelity of Simulation for Pilot Training" (Ref 24), prepared at the joint request of the Flight Mechanics Panel and the Aerospace Medical Panel, is particularly interesting, because it is the work of a group of individuals of diverse scientific and technical backgrounds

RESPONSE TO THE CHALLENGE

Early authors made problem statements and predictions to the Flight Mechanics Panel Those statements and the subsequent Flight Mechanics Panel literature can be examined to determine if the problems have been solved and the predictions fulfilled, that is, if the challenges have been met. The first paper by Pinsker (Ref. 2) predicted the early design of an aircraft system using simulation as a technique, and Westbrook's paper 4 years later (Ref 7) indicated that the challenge had been met

In AGARD's first symposium on simulation, Harper posed the three problems mentioned earlier that had to be solved in advancing the simulation technique (Ref 12) The first was the simulation hardware problem, or how to provide adequate cues to the simulator pilot. Although this problem must be faced in the design of each new simulator or simulation subsystem, advances in microelectronics have largely solved the out-the-window visual system problems by digital image-generation techniques, especially when a wide field of view is required This solution may be relatively expensive, but it is a solution

The second problem posed by Harper was the simulator computer problem--how to provide adequate computing power and at the same time constrain the computing facility to practical limits Once more, microelectronics and digital computers have solved the hardware problem It is likely that constraint is still required because of the software problems The increase in speed and decrease in price of digital computers make it possible to install a computer requiring an excessive software and programming effort

Harper's third problem was the problem of the scarcity of information about human perception--the difficulty of specifying the cues to be presented to the simulator pilot without understanding his perception of those cues A great deal of work has been done on pilot perception and pilot modeling since 1964 and many answers have been provided Experience gained in more and more simulations has provided information from which engineering solutions are derived Simulator specifiers and designers know much more about the cues required by the pilot for a given test, but it is not likely that a complete and exact understanding of man's perception and response will ever be achieved. If it should be, there would be no need for either simulator pilots or airplane pilots

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Table 1 An Assessment of Research and Development Simulators

Simulator	Complexity of real-life task[a]	Cost of simulation[a]	Confidence in results[a]
Dominant-cue	1 - 4	1 - 5	4 - 6
Multiple-cue	5 - 8	4 - 7	6 - 8
"Tomorrow's"	8 - 10	8 - 10	6 - 10
In-flight	4 - 9	7 - 10	6 - 10

[a]1 = lowest, 10 = highest

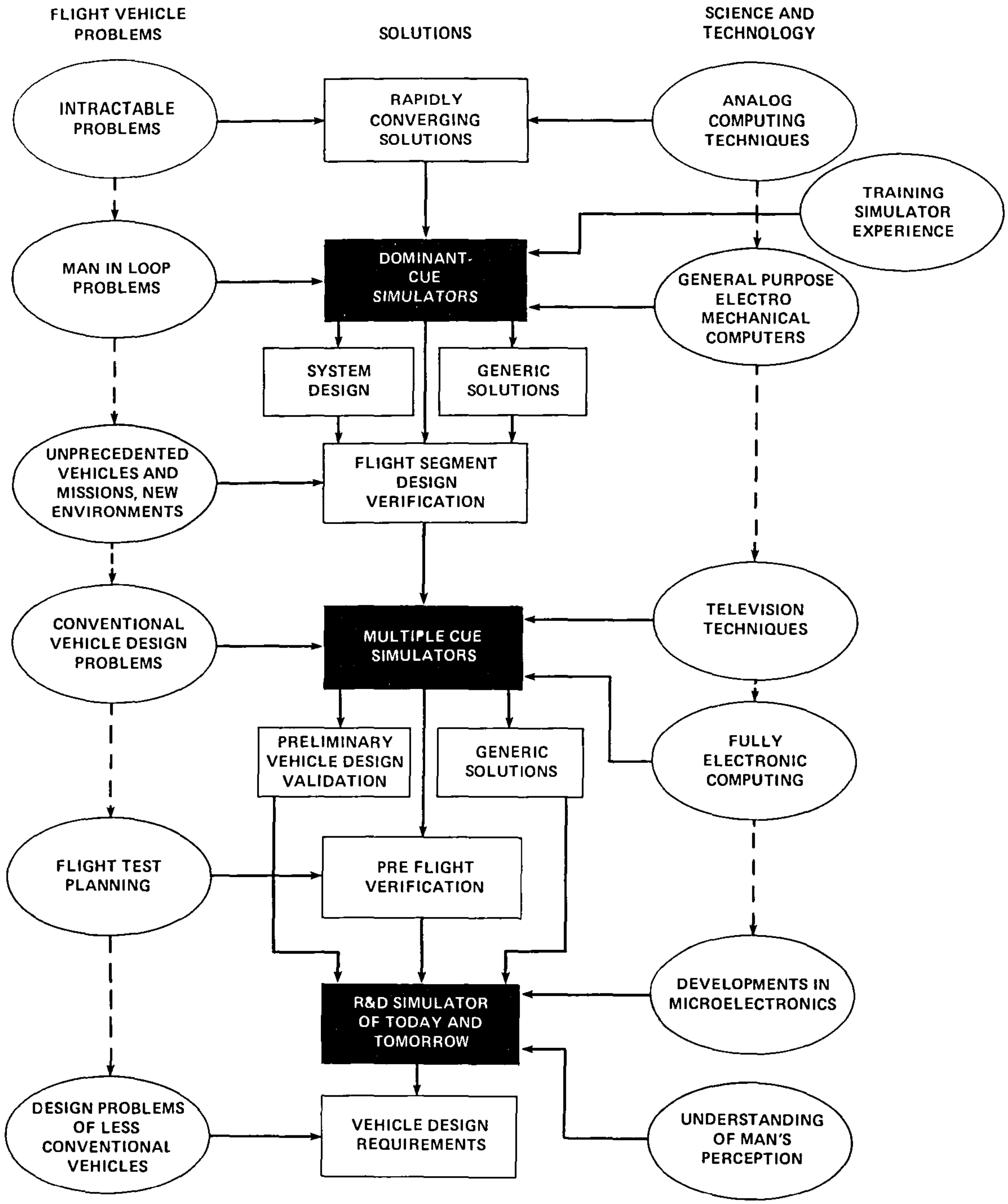

Fig 1 The development of research and development simulators.

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16. Abstract

Early AGARD papers on manned flight simulation describe the status of an emerging test technique and then offer suggestions of problems that should be solved to advance the technique and predictions of the results that will be obtained by its use. Later AGARD literature is examined to determine how these challenges have been met, both in ground-based and in-flight simulation and how AGARD has played an important role in advancing the technique so that it is now an integral part of the aerospace vehicle design process.

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