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PART 2
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DYNAMIC SYSTEM STUDIES: THE DESIGN OF A FACILITY

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AERONAUTICAL RESEARCH LABORATORY
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PROJECT 7060

WRIGHT AIR DEVELOPMENT CENTER
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

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FOREWORD

The Advisory Board on Simulation has concluded a three-year research program in air weapon system dynamics sponsored by Wright Air Development Center, with P. W. Nosker/WCRR as project engineer. This volume is one of the following 16 comprising the final report, WADC TR 54-250, entitled Dynamic System Studies:

Part No.		
1	Conclusions and Recommendations	University of Chicago
2	The Design of a Facility	" " "
3	The Mission of a Facility (Confidential)	" " "
4	Technical Staff Requirements	" " "
5	Analog Computation	Naval Ord. Lab., Corona
6	Operation & Maintenance Procedures for Analog Computers	University of Chicago
7	Digital Computers	" " "
8	Recorders	" " "
9	Flight Tables (Confidential)	" " "
10	Performance Requirements for Flight Tables	Mass. Inst. of Tech.
11	Load Simulators (Confidential)	Cook Research Lab.
12	Guidance Simulation (Secret)	Naval Ord. Lab., Corona
13	Error Studies	University of Chicago
14	Error Analysis for Differential Analyzers (written by F.J. Murray, Columbia U., and K. S. Miller, N.Y.U.)	" " "
15	Air Vehicle Characteristics (Secret)	" " "
16	Aerodynamic Studies (written by M. Z. Krzywoblocki, U. of Ill.)	" " "

The history of the project and a complete bibliography may be found in Part 1. All reports may be obtained through the project engineer.

This report represents the culmination of the assignment to determine the proper mission, equipmentation, operation procedures, and personnel for an engineering facility in the field of air weapon systems dynamics. The subdivisions of the report correspond to these four basic objectives and the subsidiary work in their support, and reflect the role of simulation as a dominant technique.

The following organizations have participated directly in the program:

Organization	Contract No.	Time of Performance
University of Chicago	AF33(038)-15068 Supplements 2 and 11	1 Feb. '51-31 Aug. '54
J. B. Rea Company	AF33(038)-15068 Subcontract 2	1 Feb. '51-31 Oct. '52
Cook Research Laboratories	AF33(038)-15068 Subcontracts 3 and 9	1 Feb. '51-31 May '54
RCA Laboratories	AF33(038)-15068 Subcontract 4	1 Feb. '51-1 Mar. '53
Armour Res. Foundation of Ill. Inst. of Technology	AF33(038)-15068 Subcontract 5	1 Feb. '52-30 Nov. '52
Northwestern University Aerial Meas. Lab.	AF33(038)-15068 Subcontract 8	17 July '52-22 Aug. '52
Mass. Inst. of Technology Flight Control Lab.	AF33(038)-15068 Purchase Order A2086	20 Apr. '54-31 Aug. '54
Mass. Inst. of Technology, Dynamic Analysis and Control Laboratory	AF33(038)-15068 Purchase Order A23883	22 July '53-30 Nov. '53
Mass. Inst. of Tech. D.A.C.L.	AF33(616)-2263 Task Statement 2	1 Dec. '53-30 Sept. '54
Nat. Bur. of Standards Corona, which became	AF33(038)-51-4345-E	25 Feb. '51-Sept. '53
Naval Ordnance Lab., Corona	MIPR(33-616)54-154	20 Nov. '53-31 Dec. '55

This is a record of formal participation only; the program was aided immeasurably by the splendid cooperation of all governmental, industrial, and educational organizations (particularly the simulation laboratories) contacted. Although it is impractical to mention them all here, the extent of their assistance is evident throughout the reports and is hereby gratefully acknowledged. Details of these affiliations, including statements of work, may be found throughout the 21 Bimonthly Progress Reports issued by the University of Chicago during the course of the work. (All formal participation in the program is recorded above; missing supplement and subcontract numbers do not pertain to this project.)

The University of Chicago was assigned prime responsibility for integration of the program. This has been effected by a full time staff at the University, and by aperiodic meetings of the following advisory committee, selected by the Air Force:

Dean Walter Bartky, Chairman	University of Chicago	1 Feb. '51-31 Aug. '54
Prof. C. S. Draper	Mass. Inst. of Tech.	1 Feb. '51-28 Feb. '53
Mr. Donald McDonald	Cook Research Lab.	1 Feb. '51-31 Aug. '54
Prof. F. J. Murray	Columbia University	1 Apr. '52-31 Aug. '54
Dr. J. B. Rea	J. B. Rea Company	1 Feb. '51-28 Feb. '53
Prof. R. C. Seamans, Jr.	Mass. Inst. of Tech.	1 Sept. '53-31 Aug. '54
Mr. R. J. Shank	Hughes Aircraft Co.	1 July '51-31 Aug. '54
Dr. H. K. Skramstad	NBS-NOLC	1 Feb. '51-31 Aug. '54
Mr. A. W. Vance	RCA Laboratories	1 Feb. '51-31 Aug. '54

ex officio:

Mr. P. W. Nosker, Project Eng.	WADC	1 Feb. '51-31 Aug. '54
Dr. B. E. Howard, Secretary	University of Chicago	1 Feb. '51-31 Aug. '54

The meetings have been recorded in the Bimonthly Progress Reports previously mentioned. Except for Dr. Skramstad, who has participated through direct arrangement between NBS-NOLC and WADC, members of the advisory committee who are not connected directly with the University have participated in the program through consulting agreements with the University of Chicago. In addition, similar consulting agreements with the University have provided for the participation of:

Dr. R. R. Bennett	Hughes Aircraft Co.	1 Jan. '52-31 Jan. '54
Mr. J. P. Corbett	Libertyville, Ill. (formerly with the University)	11 May '54-31 Aug. '54
Mr. G. L. Landsman	Motorola, Inc.	1 May '54-31 Aug. '54
Dr. Thornton Page	Johns Hopkins Univ. (formerly with the University, and Secretary to the Board until 1 Aug. '51)	7 Aug. '51-1 Mar. '53

Prof. M. Z. Krzywoblocki	Univ. of Illinois	15 Jan. '52-31 Aug. '54
Prof. K. S. Miller	New York Univ.	2 Nov. '53-31 Aug. '54
Dr. J. Winson	Riverside, N.Y. (formerly consultant to Project Cyclone	1 Mar. '53-30 June '54

Many others have contributed significantly to the progress of the work. Among those from other organizations in regular attendance at most of the meetings of the committee have been Mr. Charles F. West, Air Force Missile Test Center; Prof. L. L. Rauch, University of Michigan, representing Arnold Engineering Development Center; Col. A. I. Lingard, WADC; and Dr. F. W. Bubb, WADC.

Coordination of the program and administration of the prime contract at the University of Chicago have been under the charge of Dr. Walter Bartky, Dean of the Division of Physical Sciences and Director of the Institute for Air Weapons Research; Dr. B. E. Howard, Assistant to the Director; and Messrs. William R. Allen and William J. Riordan, Group Leaders. The work at the cooperating institutions has been directed by the appropriate member of the advisory committee and his assistants: Dr. H. K. Skramstad and Mr. Gerald L. Landsman at the National Bureau of Standards-Naval Ordnance Laboratory, Corona; Messrs. Donald McDonald and Jay Warshawsky at Cook Research Laboratories; Messrs. A. W. Vance, J. Lehman and Dr. E. C. Hutter at RCA Laboratories; Dr. J. B. Rea at J. B. Rea Company; Prof. R. C. Seamans at the Flight Control Laboratory and Dr. W. W. Seifert and Mr. H. E. Blanton at the Dynamic Analysis and Control Laboratory, Mass. Inst. of Technology. V. H. Disney, S. Hori, and G. F. Warnke at Armour Research Foundation and J. C. MacAnulty and George Goelz at Northwestern University, Aerial Measurements Lab., have directed the contributory studies at their respective organizations. More explicit credit is found in appropriate places throughout the reports; biographical sketches are in Part 1. Space does not allow full credit that is due to all the workers on the combined project, but special mention is certainly due the project engineer for his conception of the project and for his cooperation during its execution.

This volume has been prepared for publication by E. R. Spangler of the University of Chicago, who also effected the unification of format among the editing agencies. The author of this report accepts responsibility for any deficiencies in the coordination of the program and the final report, without pretending to credit for any results which may be found useful.

Special mention is due Miss Faith Mangold and Mrs. Freda Schissel for their attention to the peculiar exegencies of the typing of technical reports.

ABSTRACT

The problem of designing a facility may be conveniently subdivided into five phases: the specific tasks of determining its mission, staff, method of operation, and equipment requirements. The mission of this facility is to supply information in the field of air weapon system dynamics. To solve all the problems arising requires a staff of 60 professional persons in three branches: task teams, equipment operation, and research services. Equipment required includes a dynamic system synthesizer, general analog computers, flight tables, and load, guidance and pilot simulators. The method of operation should follow careful scientific procedures in detailed problems, and integrate with other related facilities in at least eight phases of system development.

PUBLICATION REVIEW

The publication of this report does not constitute approval by the Air Force of the findings or the conclusions contained therein. It is published only for the exchange and stimulation of ideas.

FOR THE COMMANDER:

Aldro Lingard

ALDRO LINGARD
Colonel, USAF
Chief, Aeronautical Research Laboratory
Directorate of Research

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INTRODUCTION

The purpose of this report is to summarize the technical considerations involved in the design of a system dynamics laboratory. It is written for those who wish a comprehensive introduction to the subject without reading the remaining volumes of this report and the other literature in the field. It is intended to bring together the separate reports of this project on individual subjects. The method is to discuss the background involved in each phase of the design, to summarize the essential facts; and to list the sources of information.

The design is not based on the direct personal experiences of any one individual in building and operating a laboratory, but upon a study of the experiences of many, which have been sifted and weighed and sifted again. The University has attacked the problem from an evaluation standpoint, surveying and summarizing data from all available sources, ranging from the builder of the systems to those who use them and those who specialize in solving problems encountered in their dynamic use. In addition, special detailed studies have been conducted at the University and through subcontractors to round out the picture. Parts 2 through 16 represent the final portion of this work, which we have attempted to keep on a factual level. Part 1 is a summary of the conclusions and recommendations of the advisory committee based on all available information in the field, particularly as they apply to Wright Air Development Center

1. MISSION

1.1 Discussion

The first task in designing a facility is to determine its mission. Ideally, this should be well defined beforehand. However, in a new field gaps in the developing knowledge are felt before they are articulated. Moreover, the process of selecting a staff, procuring equipment, and laying down operating procedures has a modifying feedback effect on the mission. Hence the four phases of the design must go forward together.

In this instance the original assignment (Supplement 2 to AF33(038)-15068) called for a study of control system dynamic testing by flight simulation. This work resulted in a realization that the control system is but one factor in the dynamic behavior of an air weapon system, and that simulation is but one of the important sources of information. Hence the continuation of this work under Supplement 11 called for a study of technical requirements for a dynamic system engineering facility.

The original discussions of a mission tend to be obfuscated by ricochetting chips of tradition. Persistent efforts are required to extract the technical problems from such political and administrative problems as who is interested in the field and why. However, a facility will be of more lasting value if its mission is predicated on the existence of an important class of technical problems, and this is what we have attempted to do.

1.2 Summary

We are considering a facility whose mission is to supply information in the field of air weapon system dynamics. To do this it must maintain technical cognizance over the life history of air weapon systems, exchange information with workers in the field, maintain a memory of the technology, and solve problems as required. The kinds of problems may be encompassed by the single relation $o = Si$, where i represents the input to the system, S the system operators, and o the output. Then all problems consist of finding one quantity, given the other two.

The three classes of problems are designated design, test, and evaluation,

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Manuscript released by the author in October 1954 for publication as a WADC Technical Report.

in which, respectively, the answers to the following questions are sought:

(1) What are the dynamic characteristics of a system which will produce a prescribed behavior under a given set of conditions?

(2) What is the dynamic behavior of a given system under a prescribed set of conditions?

(3) What is the range of conditions under which a given system will have a prescribed dynamic behavior?

For purposes of these investigations, the principal elements in the dynamic behavior of an air weapon system are Control and Guidance, Aerodynamics (airframe-plus-medium), and Kinematics, interacting in a closed loop.

1.3 Sources of Information

In the beginning of the program it was realized that whatever the eventual precise formulation of the mission might be, mechanical aids to analysis would be required. Hence a list of simulation and computation facilities was drawn up (56)* and a survey of these facilities begun to gather information relative to all four points of the program. The results of the survey of simulation facilities was published (29), but it was soon realized that a computation laboratory was not the kind of facility under consideration, and that survey was abandoned.

Parallel to the study of simulation facilities was a study of aircraft and guided missile problems. (J. B. Rea Co. Report FR-107, 31 Oct. 1952). Finally, liaison was maintained with the flight test facilities which are faced with similar system dynamic problems, using different tools. Originally it was conceived that the mission of the facility was to be general purpose simulation and computation, but as analysis of the problems involved progressed, it was realized that the principal concern was over the class of problems rather than the technique; and simulation is merely one important tool. Hence the final concept of the mission in terms of information in the field of air weapon system dynamics.

The details of the summary paragraph are contained in Part 3 of this report. In the course of assembling and analyzing data from other sources,

*Numbers in parentheses throughout this volume refer to the item of that number in the Bibliography.

various auxiliary studies were accomplished at the University to explore the possibilities and prove the feasibility of the specific tasks under consideration. Examples of this are technical notes on the use of simulation in operational suitability tests (76), the experimental design of tests for a particular missile (45), studies of the kinematic equations of motions (57, 69, 70, 71), and an investigation of the determination of aircraft space curves from rotational information (40, 49, 75). These are included or referred to in appropriate places in other parts of this report.

2. STAFF

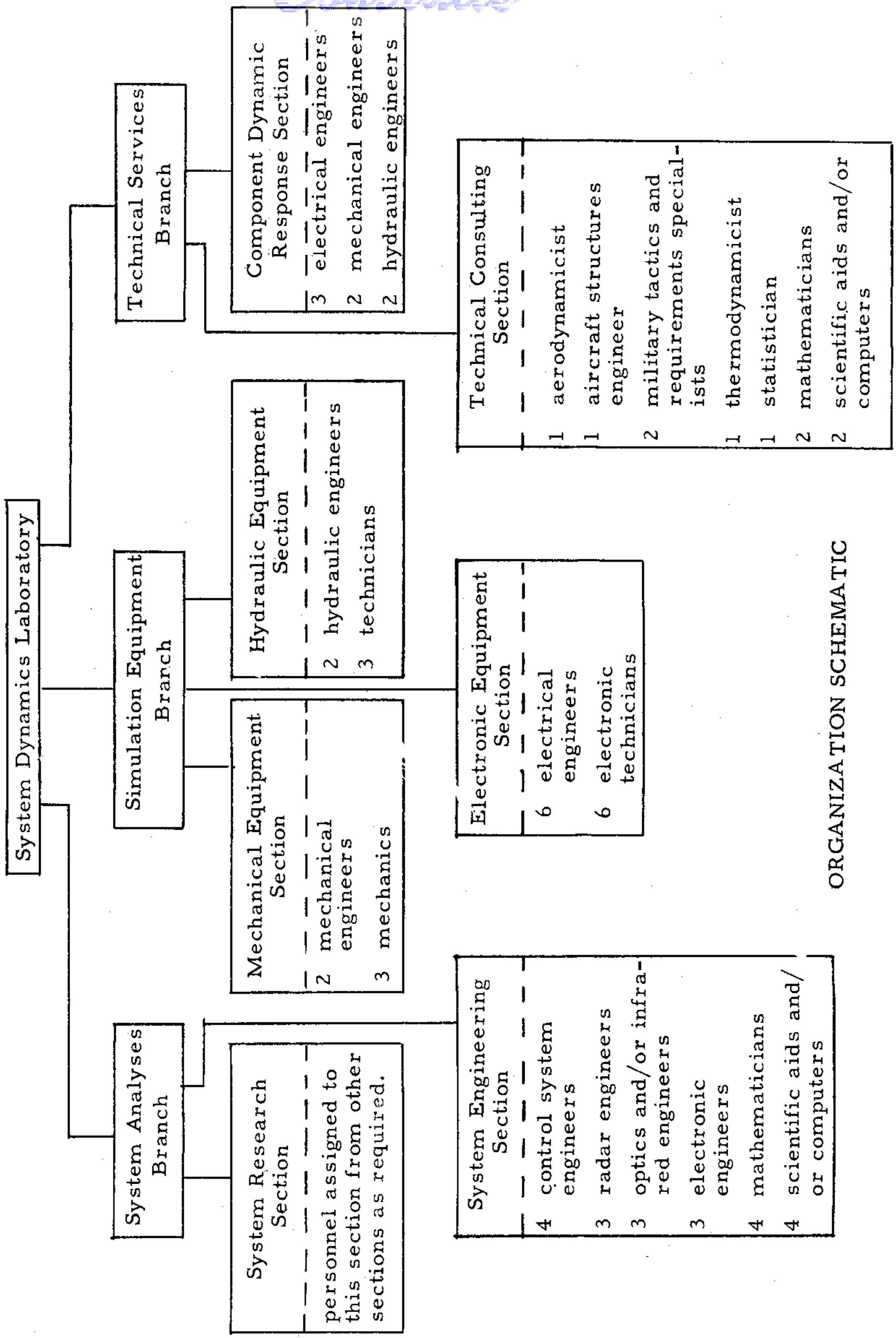
2.1 Discussion

Having determined that one is interested in the field of air weapon system dynamics, and reviewed the kinds of problems which are likely to arise, the next step in the design of a facility is to determine an appropriate staff. Since we are here concerned solely with technical requirements, we can only discuss the professional staff, although the non-professional supporting staff is vital to the success of a facility.

One of the most important items to take into consideration regarding the staff is that scientists are people, with all the frailties and foibles thereof. Since mission, procedures, and equipment can all be changed, modified, or sent back but people cannot, strict account must be taken of the limitations imposed. In the process of gathering factual information we have observed that morale is extremely important. Internal dissention and confusion regarding the goal can seriously reduce useful output. A man must feel that what he is doing is important, that he is among friends of mutual interest, and that there is a certain degree of permanence in his work and in the course the organization is pursuing. These intangibles have as real an effect as anything that can be bought at a store.

The size of a system dynamics laboratory can vary considerably in size, depending on the number of its specific task assignments within the field. For example, some of the aircraft manufacturers have system dynamics laboratories associated with the development of a single weapon system. On the other hand, some of the larger simulation laboratories specializing in one or another of the applicable techniques have solved specific task problems for many weapon systems; this also applies to the test ranges.

The staff of the facility under consideration is composed of the specialties required to accomplish the tasks listed under mission. In combining the experiences of the various sources of information, a good test of the talents required consisted of observing which questions were asked of others, and which others asked of them. In this way the problems of interest were matched with the talents required in solving them.



ORGANIZATION SCHEMATIC

2.2 Summary

A professional staff capable of accomplishing the stated mission successfully consists of approximately 60 people. These may be grouped in three branches, corresponding to the three basic types of activity involved. The accompanying chart summarizes the organization contemplated.

2.3 Sources of Information

The details of the summary paragraph are contained in Part 4 of this report. The information represents an analysis of a survey of system dynamic laboratories, and of the problems of air weapon system dynamics. Again in the course of the analysis of data from other sources, specific studies were conducted at the University to supply missing information. An example of this type is the study of a problem of queues with many servers and different types of customers (6), which is an abstraction of the problem of the optimum number of technicians needed to keep equipment repaired and operating. Two other studies of interest in staffing any research organization are Scientific Research: Its Administration and Organization, edited by G. Bush and L. H. Hattery (Washington, 1950), and Research in Industry, edited by C. C. Furnas (N.Y., 1948).

3. EQUIPMENT

3.1 Discussion

Having decided on a class of problems needing solution and the kinds of people required to solve them, the next question in the design of a facility is whether or not any specialized equipment is required. This affects the size of the staff, the building, and the budget.* The ideal situation is when the staff can supply all the information desired by purely theoretical means. But in the field of air weapon system dynamics this is not the case.

Besides theory, the main sources of system dynamics information are flight test and flight simulation. Sources of component dynamic information are the wind tunnel for the airframe, motor test stand for the motor, rate and oscillation tables for rotational motion sensitive elements, sleds or tracks for translational motion sensitive elements, and the like. These component test devices attempt to reproduce the aspects of the environment pertinent to the component under consideration ("simulate" the environment), with a view toward obtaining the component's open loop response characteristics. The distinguishing feature of flight simulation is that the closed loop behavior of the entire system is brought under close scrutiny; the simulation is either of the environment of the real component, or of the component itself.

Since equipment is expensive, the design of a facility must be realistic with respect to two factors: (1) which of the applicable devices are to be in sufficient use by the staff or whose use is of such a nature as to warrant the physical adjoining of these devices to the staff quarters, and which of the devices need merely be accessible, though at a distance; and (2) which of the devices exist in sufficient abundance to supply the necessary information, and which do not. Of course no sharp line can be drawn in considering either of these factors, and whatever the present situation, it will slowly change with time.

Nevertheless, the general situation with respect to sources of information on system dynamics may be summarized as follows.

The problems of flight testing, while many, are being pursued vigorously

*The chart summarizing the staff requirements reflects the kinds of specialized equipment needed.

and have been for some time. The techniques of flight simulation are relatively new. Consequently this study has concentrated on the latter aspects of system dynamics. Similarly, component test equipment is being studied in its own right, and it has been assumed that information from wind tunnels and motor test stands is likewise accessible for system dynamic studies.

On the other hand, the apparatus of flight simulation is either in such constant use that its physical nearness is a distinct asset, or it is of such nature that it must be operated in conjunction with the staff and/or other pieces of apparatus. It is this class of equipment which has received our special attention.

For flight simulation purposes the air weapon system can be subdivided into the Aerodynamics and Kinematics (airframe, propulsion and medium), and the Control and Guidance subsystems. The former are simulated in the laboratory; the latter may be brought into the laboratory and operated in a simulated environment. All the subsystems must be interconnected in order that the dynamic behavior of the entire system may be observed.

An objective in designing a facility is to select the best tool for each job. The dynamic simulation of an air weapon system involves two basic types of apparatus, corresponding to the two subsystems listed above. The two types of apparatus we will call mathematical and physical. The Aerodynamics and Kinematics are simulated by constructing a mathematical model, which is then physically realized by an appropriate device, a device which solves the special equations of the mathematical model subject to certain stringent conditions. The Control and Guidance may also be simulated mathematically; there is also a class of physical apparatus which simulates the flight environment of the real Control and Guidance subsystems. The necessary items in these two categories are listed under Mathematical Simulation and Physical Simulation in the following summary.

3.2 Summary

3.2.1 Mathematical Simulation. The Selection of a Computer. There are many types of mechanized methods on the market today for solving equations. The basic types are digital, analog, and a combination of the two. The digital devices include the desk calculator, punched card calculators, and the large sequence controlled calculators, called simply digital computers. The analog devices include the operational amplifier type, the passive network analyzers, and the so-called "fast-time" computers. The digital differential analyzer is an example of combined digital and analog operations.

The general operational characteristics of the digital and analog computers are quite different. Simply stated, the digital device can be made as accurate as desired, but its speed is limited by certain physical restrictions. The strictly analog device operates naturally in real time* with an adjustable time constant, but its accuracy is limited by the physical precision of its components.

For simulation purposes, it is necessary to operate in real time whenever real components are being employed, and hence we are led immediately to an analog device as one of the basic tools of system dynamics. Because of its greater accuracy, the digital computer is useful for check purposes and for such general mathematical equations as may require solution from time to time.

Of the analog devices, the passive network analyzers are restrictive since in them it is difficult to make system changes, whereas the nature of the aerodynamic and kinematic equations imposes certain conditions not generally anticipated or realized by the completely general analog computer. Therefore one of the principal tools in air weapon system dynamics is a device to simulate or synthesize the dynamic system behavior, a dynamic system simulator or dynamic system synthesizer. Other particular problems have corresponding devices best suited to these tasks. Following is a summary of the major pieces of equipment of this type which have been found to be important in system dynamics.

3.2.1.1. Dynamic System Synthesizer. The solution of a wide class of system dynamic problems requires a device which can solve the complete set of differential equations of motion of the system in real time. This involves the equivalent of approximately 600 mathematical operations. The operating characteristics of the device should include reliability, repeatability, rapid problem setup, convenient problem storage, and as much flexibility as is compatible with its mission. The kinematic equations, at least, must be

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* A device is said to operate in real time if it obtains the numerical value of a function of time, at time t, in a period of time not greater than t.

solved with a degree of accuracy that involves special programming (44). A few such devices exist which approximate these requirements in many but not all particulars, and have proved invaluable.

3.2.1.2. General Purpose Analog Computers. Operational amplifier type computers of the REAC, GEDA, or EA type are employed in every system dynamics laboratory and are essential in any laboratory design.*

3.2.1.3. Fast Time Computers.** This equipment includes analog computers (usually small and flexible) with circuit time constants of such a value that the solution is repeated several thousand times per second, the solution usually being displayed on an oscilloscope. The parameters can be varied while the solution is being displayed so that immediate effects of the parameter changes on the solution can be seen, i.e., it is ideal for twiddling. If a permanent record of a particular result is desired, the oscilloscope can be photographed.

3.2.1.4. Passive Network Analyzers. Equipment of this type can be used to reduce the number of operational amplifiers needed for a given problem. The passive network is excellent for simulating systems governed by systems of partial differential equations, such as heat flow problems.*** Direct analog devices can be used to simulate such phenomena as aeroelasticity (36).

3.2.1.5. Digital Computers. Occasional problems of a purely mathematical nature and spot check solutions of analog computer problems require the use of digital computers. Any large computation center with a good large scale digital computer can provide the necessary services (58).

3.2.2 Physical Simulation. The control and guidance subsystems encompass those parts of the air weapon system which can be brought into the laboratory for closed loop dynamic study of the system. To do this we must simulate the environment of these devices in the laboratory. The principal elements of control and guidance are: (1) control surfaces and their actuators, (2) the pilot, and (3) the reference elements. The latter include references to (a)

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* Reeves, Goodyear, Electronic Associates. See 3.3 infra.

** As in the M.I.T. Instrumentation Laboratory.
Section 3.2.1.3 is adapted from Volume IV of the Summary Progress Report (26).

*** As done by Dr. V. Paschkis of Columbia University.

inertial space (gyros and accelerometers), (b) the stars (stellar navigation), (c) the earth (radio, map, and magnetic navigation), and (d) a target (the radiation information and the target motion). The appropriate environmental input to any or all of these which appear in a given system must be simulated in the laboratory.

The apparatus involved is at present in three general states: (1) general purpose apparatus which can be specified in sufficient detail to allow procurement, (2) general purpose apparatus which is still under development, and (3) special purpose apparatus which must be developed with the device whose environment it is to simulate. Following is a summary of the major pieces of apparatus of this type which have been found to be important in system dynamics.

3.2.2.1 Flight Tables. These devices (sometimes called flight simulators) are used to simulate the environment of attitude sensing elements, i.e., with the attitude sensing elements mounted upon them they can assume the proper angular oreintation in response to a given command. The elements mounted on a flight table are of two types: (1) those which try to measure variation from a fixed attitude in space, as typified by gyros and stabilized platforms, and (2) those which try to maneuver, as seeker type systems. For both types of elements, the flight table must be able to reproduce accurately any angular motion possible for any system it is used to study. This is too much to expect of one flight table. However, two flight tables, one small and swift, the other large and powerful, can cover the range.

In addition to flight tables which can assume arbitrary orientation (usually accomplished by three gimbal axes), one- and two-axis flight tables are useful for studying separately the longitudinal and lateral (in and not in the aircraft plane of symmetry) modes for small excursions.

3.2.2.2 Load Simulators. When the actual control elements of the air vehicle are incorporated in a laboratory dynamic system test, the control surfaces and/or actuators must be acting against the same aerodynamic reaction they would be experiencing in flight. The device which accomplishes this is the (aerodynamic) load simulator. The range of aerodynamic loads from the smallest missile to the largest bomber is enormous, and no one load simulator can handle the range. To the first order approximation the air reaction is proportional to the displacement, and hence small loads can be simulated by a linear spring. Larger loads may be obtained more accurately with larger springs with servo trimming, but beyond a certain range the only practical device is a servo-controlled load simulator. A difficulty arises from the fact that such a device is a two-input system, i.e., the load produced is a function not only of the load demanded but also of the velocity. Hence velocity feedback is required to improve the dynamic response.

3.2.2.3. Guidance Simulators. The environment of a guidance system includes the character of the received radiation energy, the relative target motion, and the inertial attitude of the parent vehicle. The last item is handled by mounting the attitude sensitive guidance elements on the flight table. Other devices are required to simulate the remaining aspects (except inertial) of the guidance system environment in the laboratory. The radiation involved in the system may be light, infrared, radar, or sound; a similar choice exists for the simulated system, and theoretically any one of the four may be used to simulate any of the four; many of the combinations do exist, sound and light, for example, both simulating radar. There are many ways of simulating relative target motion: vertical target carriages, horizontal target carriages, semi-spherical target carriages, moving mirrors, moving light beams, and changing relative phase patterns.

There are indications that the guidance subsystem may very well prove to be an important limiting factor in future air weapon systems, and therefore it is important that means be provided for including it in system dynamic tests. However, it seems that the only provision that can be made is to provide quite a bit of extra floor space. No commercially available guidance simulation equipment now exists capable of adaptation to the general purposes of a system dynamics laboratory. Rather than obtain a special piece of equipment which may never be used, it seems best to arrange for the development of simulation equipment concurrently with the guidance system.

3.2.2.4 Pilot Simulation. The pilot is an all-important component in the dynamic behavior of a piloted air weapon system. Questions regarding the dynamic behavior of such a system cannot be answered without including the pilot in the system. There are three ways of doing this: simulate the pilot, simulate his environment, or cancel his insurance policy. Not enough is known about the pilot to make either of the first two schemes entirely satisfactory, and there are difficulties of measurement in the third. The pilot is being studied with respect to the first two schemes: the first, in the hopes that, if a pilot's reactions under a given but limited set of circumstances can be understood, he may be simulated in respect to those circumstances; this approach has some hope; the second, in the hope that a sufficiently realistic flight environment can be reproduced in the laboratory. This last is the problem of flight training. For system dynamic studies, however, it is likely the pilot has too many intangible inputs to fool successfully.

3.2.2.5 Auxiliary Equipment. Besides the apparatus simulating the sytem or its environment, auxiliary apparatus must be considered. It is unimportant whether we have a laboratory device capable of representing the dynamic behavior of a weapon system, unless we can tell it what to do, observe its operation, and record and analyze its results. That is, we must consider input-output apparatus and further data reduction devices.

Sometimes a given marginal item (e.g., a function generator) is referred to indiscriminately as part of the simulator or auxiliary equipment. To clear up this matter we lay down the definition that the simulator consists of all those, and only those, items which together represent the device governed by the same set of equations as the system under investigation. Thus, a function generator is part of the simulator, for without it the proper equations are not being solved. A recorder is not part of the simulator, for its removal does not affect the set of equations being solved.

The inputs to the system are commands, noise, and target motion.* The commands (which may be no more than stated initial conditions) and programmed target motion are relatively easy to handle. Noise generators, while they are coming to be extremely important, we avoid like poison. There are some, but the statisticians do not seem to agree on what they represent.

The output of the system is the continuous trajectory of the system, or its value at one point (miss distance). This information must be recorded in useful form by an appropriate device. This takes into account the fact that

*See Appendix 1, Part 3.

flight simulation can produce an enormous quantity of data, and that further analysis of the data may be required (e.g., statistical and error studies) by other appropriate devices (usually a digital computer).

It turns out that three kinds of record are desirable: continuous visual record against time, space record, and quantized data for further processing. The continuous record against time should be instantaneously visible, and have certain speed and accuracy characteristics. No one device satisfies both requirements, but pen-drum recorders satisfy the one, and oscillographs the other. For a space record, only two dimensions at a time are practical, and a plotting board does this. For the quantized data, analog-to-digital converters are required. There are many types* but none with sufficient accuracy requirements. A design exists, however, and production feasibility is claimed with proving studies under way.

3.3 Sources of Information

The details of the summary paragraphs are contained in Parts 5, 7, 8, 9, 10, 11, and 12 of this report. These, in turn, refer to volumes of the Summary Progress Report (24, 25, 26, 28). (Occasional remarks are copied directly.) The material in these works is based on an analysis and evaluation of the experience of others, as obtained from the surveys of pertinent organizations, and special studies of various details conducted by the University and its subcontractors. Examples of these are studies made at the University and reported in the indicated papers, as listed in the Bibliography:

Equipment in general: 66.
Analog computers: 36, 37, 38, 44, 51, 60, 67, 69, 70, 71.
Digital computers: 54, 58, 59, 65.
Flight tables: 37, 38, 47, 48, 50.
Load simulators and flight tables: 42, 51, 64, 72.
Guidance simulation: 39, 41.
Pilot simulation: private communcations with
Goodyear Aircraft Corp. (R. Mead) and
the Franklin Institute (E.S. Krendel).
Recorders: 68.

Part 8 (recorders) represents an analysis of literature received from the 185 manufacturers of recording equipment listed in the IRE directory.

*See G. L. Hollander, "Criteria for the Selection of Analogue-to-Digital Converters," Ph. D. Thesis, M.I.T., 1953.

4. PROCEDURES

4.1 Discussion

The process of designing a facility must include planning its method of operation. In this connection there are two general areas of consideration, which we will designate procedures in the large, and procedures in the small. Procedures in the large refer to the sequential relationship among separate tasks in the field of air weapon system dynamics, while procedures in the small refer to the operational process of solving a specific system dynamics problem.

4.2 Summary

4.2.1 Procedures in the Large. A study of the development of many air weapon systems makes clear that dynamic problems appear at several stages of their life histories. An analysis of the kinds of problems appearing leads to the grouping described under mission. Further study fails to reveal any unifying principles regarding procedures. Each weapon system is unique in the sense that its development has as many deviations from any "average" procedural development as it has agreements.

One possible idealized sequence of points of applicability of dynamic system information is the following:*

1. Preliminary analysis and synthesis on the basis of rough data.
2. Construction and testing of items of hardware.
3. Determination of flight performance by means of mathematical simulation, and correction of deficiencies thereby discovered.
4. Determination of closed loop performance by means of physical simulation.
5. Comparison of mathematical with physical simulation and repetition of steps 2, 3, and 4 to attain optimal preflight design.
6. Flight tests.
7. Analysis and interpretation of the correlated results of steps 3, 4, and 6.

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*From Vol. I, Summary Progress Report.

8. Determination of complete performance characteristics.

It must be emphasized that this sequence is idealized, and that any given system will deviate in some important particular.

A more elaborate information flow diagram for the development of an instrument system (equally applicable here) has been constructed by Draper.* This chart (with typographical corrections) could be a profitable mural on the wall of every system laboratory.

4.2.2 Procedures in the Small

4.2.2.1 Analog Simulation. Getting useful results from analog computation calls for careful study of (1) the limits of the problem representation, (2) purpose to which computational results will be put, (3) suitability of the computer for the problem, and (4) methods for preventing and discovering malfunctions on the part of both operating staff and computer. There is no substitute for careful scientific procedures in obtaining such useful results.

Close cooperation between a specialized computer staff, that knows how best to use the computer, and the design staff, that knows the physical problem and its mathematical representation, will aid in assuring useful results from analog computation.

It may be necessary to do some experimentation in order to determine the most desirable maintenance procedures for a given computer facility.

4.2.2.2 Physical Simulation. Very little can be said about specific detailed procedures for solving physical simulation problems. One useful source of information is an unpublished volume of the M.I.T. Flight Simulator at the Dynamic Analysis and Control Laboratory. Most problems are unique, so that little else that has been analyzed and/or routinized from the procedural standpoint is applicable.

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*C. S. Draper, W. McKay, S. Lees, Instrument Engineering, Part I, M.I.T., Cambridge, Mass., Sept. 1951, pp. vi-vii.

4.3 Sources of Information

The details of procedures in the small for analog simulation are contained in Part 6 of this report, which is partly based on data from the many companies acknowledged there. The M.I.T. Flight Simulator is a source of information on flight table procedures. Procedures in the large is based on Volume 1 of the Summary Progress Report, and Part I of the M.I.T. volume entitled Instrument Engineering. Some of the best known examples of dynamic system engineering in the development of a weapon system appear in Appendix 5, Part 3. Particular studies at the University on the subject are items 30, 35, 45, 46, and 63 in the Bibliography.

5. RESEARCH

5.1 Discussion

In pursuing the basic four-point program in the design of a facility, it has been found necessary to support continuing research to supply needed auxiliary information. The basic categories of research were (1) the survey of air vehicle characteristics, (2) survey of simulation and computation facilities, (3) aerodynamic studies, and (4) error studies.

5.2 Summary

5.2.1 Survey of Air Vehicle Characteristics. Early in the program a continuing survey of air vehicle characteristics was begun as the "what to simulate" phase of the program. The object of this work has been twofold: (1) to obtain, summarize, and extrapolate design data on air vehicles to aid in determining design data for simulation equipment and (2) to study the development of the air vehicles with a view toward isolating the important system dynamics problems.

The first study culminated in Part 15 of this report, which contains summarized design data on 39 Air Force, five Army, and 28 Navy vehicles. Although the data is digested in such a way that no specific vehicle can be distinguished, it is still Secret and cannot be presented here--in fact, how can one summarize a set of numbers?

The second part of the work is contained largely in The J. B. Rea Co. Final Report 107. This contains descriptions of systems and their development which have not been released by the contractors as non-proprietary, but a summary of the problems requiring simulation appears in Part 3 of this Dynamic System Studies.

5.2.2. Survey of Simulation Facilities. Early in the program a survey of simulation and computation facilities was begun under the "how to simulate" phase of the program. The survey of computation facilities was abandoned when sufficient data had been accumulated to make apparent that this was not the type of facility under consideration. Data on digital computers was useful, however, in studying the equipment tools for system dynamics.

The Survey of Simulation Facilities (29) represents the summary of information accumulated to 1952. This has particular emphasis on equipment components. Periodic resurvey of these facilities and the various system dynamic laboratories which have been growing rapidly throughout the country has furnished the raw data for the mission, personnel, and procedures conclusions.

5.2.3. Aerodynamic Studies. Many of the question which arise in the design of a facility have their answers in the analysis of a wealth of data already available. However, to simulate the dynamic behavior of an air vehicle one must have expressions for the forces acting upon it, and there was no ready answer to this question which was deemed satisfactory for simulation purposes. Consequently an investigation of the forces acting on an air vehicle was begun.

One of the results of the investigation is that at present the aerodynamic forces on an air vehicle are represented by algebraic expressions of 10 independent variables: the six degrees of relative air motion and their derivatives, the three control variables, and altitude. The expressions involve auxiliary variables such as angles of attack and velocity of sound (in the form of Mach number) which are functions of the 10. The expressions are Taylor series expansions of unknown functions, with coefficients determined by wind tunnel measurements and curve matching.

For the direction present development is taking, sounder theoretical knowledge is desired. This appears possible by adapting the differential equations of fluid motion, continuity, energy, and state in such a way that the forces are generated by a force simulator in the form of D.C. voltages in the same way that trajectories are generated by the motion simulators without the explicit expressions for either.

5.2.4. Error Studies. Throughout all the investigations leading to the design and subsequent operation of a facility two questions constantly appear: "How good is this equipment?" and "How good is this answer?" An adequate error theory is required to answer these questions.

Part 14 of this report constitutes a mathematical framework for the study of errors. It has been applied (Part 13) to problems of specifying equipment characteristics for a facility, and methods of evaluating the reliability and accuracy of solutions of system dynamic problems have been investigated. A routine procedure for determining these quantities for each problem solved in an operating facility is needed; it does not yet exist, but it appears feasible. Present error theory can determine the modal behavior of machine solutions; the principal need today is for information on the effect of nonlinear components on stability.

5.3 Sources of Information

It is impossible to list here the organizations contacted in the surveys. Credit is given in Parts 4, 6, and 15 to many of the organizations who have kindly given of their time and data, and items 75 and 76 are useful to anyone making le grand tour.

The paragraph on aerodynamic studies summarizes the material in Part 16 of this report. Through a series of aerodynamic studies (1-9), a record has been maintained of the continuing survey and analysis of the literature.

The paragraph on error studies is detailed in Part 13 and 14 of this report, and Volume V of the Summary Progress Report (27). Particular studies conducted during the program are contained in several University Technical Notes (34, 43, 44, 48, 74).

Besides the compilation and digestion of air vehicle characteristic data in Part 15, which was obtained from the manufacturer, a sequence of technical notes containing condensed non-proprietary data on specific air vehicles has been under way (31, 32, 33).

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