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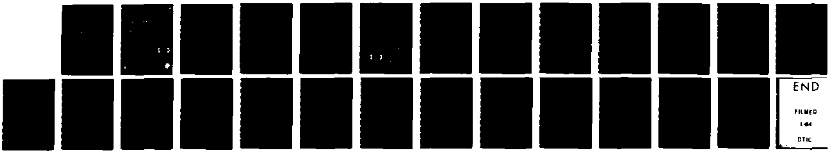

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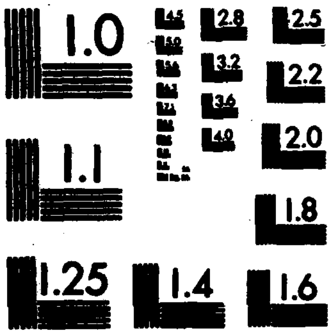

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AD-A135 590

SCIENCE OF INTEGRATION

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Prepared for
USAF SCHOOL OF AEROSPACE MEDICINE
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NOTICES

This final report was submitted by Bioengineering and Industrial Engineering Divisions, Texas A&M University, College Station, Texas 77843, under contract F33615-78-D-0629, Task order 58, job order 7930-14-48, with the USAF School of Aerospace Medicine, Aerospace Medical Division, AFSC, Brooks Air Force Base, Texas. Dr. Russell R. Burton (USAFSAM/VNB), was the Laboratory Project Scientist-in-Charge.

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The Office of Public Affairs has reviewed this report, and it is releasable to the National Technical Information Service, where it will be available to the general public, including foreign nationals.

This report has been reviewed and is approved for publication.

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This project identified under the term "integration," rules, guidelines, and management processes which, when followed, would result in optimal system performance and the avoidance of certain types of problems which presently exist in aircrew life support equipment. The occurrence of burdensome or otherwise problematical equipment is frequently a result of poorly defined design constraints rather than lack of integration. Therefore, lack of integration is not necessarily the cause of equipment problems, nor will integration necessarily alleviate them. Integration, the combining of tasks or system hardware so as to

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20. ABSTRACT (Continued)

optimize a system design with respect to preselected parameters, requires a detailed specification of the critical parameters and sufficient design alternatives such that the optimum design can be selected. Integration requires an approach in which several designs which meet the functional requirements are developed and at least conceptually tested against the constraints and parameters requiring optimization. Suitable methods or types of integration depend on the type of system being designed (e.g., electrical, mechanical, hydraulic, etc.), and the relevant design rule is simply to minimize the number and types of tasks and/or the amount of hardware necessary to achieve the functional design objectives. Both technical and managerial research, development, and implementation control are necessary to (a) properly define subsystem design constraints, (b) identify existing subsystems that can or must be redesigned to accommodate other new subsystems, and (c) test any resultant system for overall compliance with total function and total constraints.

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SCIENCE OF INTEGRATION

INTRODUCTION

The design of complex, human-operated (man-machine) systems, especially when these systems are subject to evolutionary change including add-on functions, tasks, and hardware, presents a number of challenges to the design/management team. Without "good engineering" and established procedures to control the engineering function, the design process can break down in a number of ways. With respect to function the continual addition of new functions may result in redundancy, incompatibility, or excessive complexity with its concomitant high cost and reduced reliability. The addition of operator tasks may result in an excessive overall burden on the operator, tasks that interfere with each other, or tasks that either cannot be performed or cannot be performed correctly under real operational conditions. Hardware problems can include excessive weight, excessive bulk, excessive power consumption or heat dissipation, direct interference between separate hardware functions, and problems with reliability and maintainability.

Many of these problems have been observed in the development of Air Force life support and protective equipment. In the past each piece of equipment has often been developed independently, usually by different companies, and over different periods of time. Thus the existing system is a composite of "quick-fix" and "add-on" approaches to overall system development. As a result, systems are complicated, costly, bulky, weighty, and, in many cases, aircraft specific. These systems can adversely affect pilot performance and safety, can be a logistical nightmare, have high life cycle costs, and have less than optimal reliability and maintainability. Furthermore, these systems are not presently fixed, and the processes by which they arrived at their current status threaten to continue to produce add-ons which may have detrimental overall impact.

Recognition of this continuing problem was the motivation for this research project with the main objective to identify, under the term "integration," those rules, guidelines, and management processes that when followed would result in improved system performance and avoidance of the problems.

Consistent with the objective of the research, a review of the available literature and current practice was made under the headings of "systems" and "integration." It is noteworthy that despite the widespread use of the terms "system" and "integration" little relevant literature was found. In fact, the terms are now so widely used for such a broad spectrum of subjects that they have become totally ambiguous. As used here, <u>system</u> will mean a collection of interrelated components unified by design to obtain one or more objectives. <u>Subsystem</u> will denote a part of the system which is separately identifiable by function, design, or both. The interrelated parts of a system can be considered by definition to be at least <u>interfaced</u>; that is, they are connected together in some way such that the collection exists as an identifiable set. Beyond such interfacing it is desirable, if not essential, that the system be integrated (to be defined later).

Parallel to the literature review an effort was made to contact other industries and agencies that were perceived to have analogous problems and to ask them what guidelines they had, written or otherwise, in this area. Again there turned out to be a dearth of useful information, even from organizations that had "integration" as part of a group or job title. Typical responses ranged from "good luck" to "it's just good engineering." The closest thing to what was sought was configuration control, but that is concerned with management and paper flow rather than engineering achievement.

With the failure of the traditional resources of published literature and personal contact, and having a problem which was not amenable to an experimental or analytical attack, the only remaining approach was one of individual and group contemplation.

Since the problems identified here, and the proposition that integration will address these problems, are issues in engineering design, a review of aspects of the engineering design process is necessary. This review will be followed by a definition and discussion of integration.

DESIGN

The engineering design process always begins with a set of objectives which the proposed design must achieve. These objectives must consist of two major parts. The first part is the function or functions that the resultant system or subsystem must achieve. The second part is the constraints on the system. Physical constraints may include weight, size, power requirements, heat dissipation, etc. For man-machine systems additional constraints may be in the form of the number and kinds of tasks that can be placed on the operator. These task constraints may relate to the number and kinds of other tasks that the operator may also need to perform and/or the ability of the operator to perform tasks under real operational conditions. Other constraints may result from the conditions of use of the system. Additional constraints are in the form of reliability and maintainability considerations, and, of course, cost is commonly also a constraint.

Function

The functional requirements can generally be considered as absolutes; that is, the system must be able to perform the stated function. It cannot partly perform the function nor is it necessarily required to perform more than the required function. However, functional requirements should at times be open to review with respect to reasonableness of the function and feasibility of its achievement under the given system constraints.

An example here might be a requirement for head impact protection. Assuming the requirement is rational, the design must achieve the desired degree of protection. A lesser degree of protection is not acceptable and would represent a failure of the design to achieve the stated goals. A greater level of protection might be desirable but would probably involve more weight or bulk than necessary to achieve the required protection, and therefore it may be more desirable to reduce the weight or bulk rather than provide the overdesigned system. If the functional requirement is not feasible within the design constraints, then either the functional requirement or the constraint must be subjected to further review. It must be noted here that feasibility may be a function of the talents of the design team; i.e., what is infeasible for one group may be feasible for another.

With complex systems the performance of each and every function must be assured such that the functions are not only achieved independently but are also achieved sequentially or simultaneously as required. Furthermore, they must function under the real operational conditions. Thus the design of an ejection seat release mechanism which requires the operator to activate a particular control may appear to meet the narrowly defined requirements of the release mechanism itself. However, if under real conditions the operator's hands are engaged in other tasks when the need for ejecting occurs, or if the operator cannot move his hand to activate the control under certain conditions, then the design of the ejection seat release mechanism is unacceptable, at least for some operational requirements. The other activities which the operator may be engaged in and the existence of G forces which interfere with the operator's performance represent constraints on the system and subsystem design that should have been accounted for in the ejection seat release mechanism design constraints.

Constraints

All design projects are subject to constraints of various kinds. Some of these constraints may take the form of limits (maximums or minimums) rather than the absolute form of the functional requirements. Thus a helmet for head protection may be limited to a certain weight, and therefore the resultant design must weigh no more than the specified amount. A helmet which achieves the functional protection requirement but weighs more than the specified weight is not an acceptable design. In this case the helmet must be redesigned or the weight limit reopened for further consideration. Other limit constraints may be in physical factors such as size, thermal, or acoustic characteristics. Reliability and maintainability can also be expressed in the form of limiting values.

Task constraints are of great importance in the design of complex man-machine systems. It must be known in advance what the system operator is capable of achieving in terms of level of performance, duration of performance, reliability of performance, etc., with respect to all tasks which must be performed. It must also be known what influences operator capability and performance such as conditioning, training, stress, and perceived comfort.

In the case of aircrew systems the conditions of actual use of the system are of critical importance. It is therefore necessary for the designer to have knowledge in the form of complete scenarios of what is taking place in the environment prior to or during the time when a system function or operator task performance is to occur. Environmental influences may include acceleration, vibration, temperature, light level, chemicals, fire, equipment malfunctions, and ultimately enemy attack. Clearly any design which results in a system or subsystem whose functional capability is such that it works when tested under unrealistic mock or simulated conditions but fails to function under operational conditions is an unacceptable design which has not met what should have been correctly stated design requirements.

In some cases it may be possible to achieve a design that meets the functional requirements, physical and task constraints, but only under a subset of the possible operational environments. Such a design is at the onset unacceptable but it may be appropriate to accept the design with the understanding that it does not meet the original design objectives. This approach can be looked at as either a restatement of the constraints so as to allow the design to conform or as an acceptable exception to conformity. The former procedure is dangerous in that if the original constraints were rational, downgrading them may be questionable. In the latter case the restrictions on acceptable ranges of utility will have to be "remembered," and if this approach is allowed, it is conceivable that many of the subsystems will have different regions of acceptable performance. Serious management and operational difficulties may result.

Information Availability

Rational design requires the availability of a complete statement of all functional requirements or a correctly isolated statement of a single functional requirement. It also requires a complete statement of both physical and task/operator constraints. And finally, the requirements and constraints must be put in the context of actual conditions of use. Some of this information may not always be available and may be subject to ongoing research or provide the basis for new research directions. Where adequate knowledge is lacking, it may be appropriate where possible to identify those aspects of the system constraints that are unknown and likewise to identify those aspects of a resultant design that may be inadequate under conditions that have not yet been properly identified. This identification can be especially important in systems subject to evolutionary or add-on design where the system at any point in time may include both proven and unproven designs and in which the addition of new functions, tasks, or components may exacerbate the limitations of the existing system.

Unknown aspects of the operational environment also present serious limitations to the probable success of aircrew systems. In particular, when operational requirements change, there should not be automatic expectation that the existing system will continue to perform or that a few quick fixes or add-ons will be adequate to account for the effect of the changed operational environment on system and operator performance.

Add-on vs From-Scratch Design

Two design approaches are relevant to the present discussion. In one design approach the work begins without constraints due to previously existing hardware; that is, the design proceeds "from scratch." In the case of aircrew life support equipment this approach could mean either without constraints due to the existing aircrew worn or operated equipment, or in an even broader sense, the design could proceed without the constraints of the existing cockpit and aircraft-mounted equipment; that is, the cockpit system would be designed simultaneously with the aircrew equipment.

Design from scratch presents a broad opportunity to continually produce a system which meets the overall functional and constraint criteria. It does not, however, insure that the design will achieve total success. Depending on the scale of the system the control of such a design approach can be very difficult due to the scope of the work and the number of designers needed. The somewhat unfortunate response to this challenge is to subdivide the total design project into smaller units. This kind of modularization apparently allows redefinition of the design problem into more workable units. To be effective, this redefinition process requires distribution of system constraints and other design criteria, and the establishment of interfacing requirements. These interfacing requirements can be as simple as the location and size of bolt holes or the type of electrical connector to be employed. They can also involve communication and coordination requirements for between-module functions and operator/module interactions. Such a modularized system may superficially look well designed, but it may not result in an optimization of the total package. For example, a number of units may have batteries whereas an alternative design may have allowed a single battery (with appropriate considerations of redundancy). A modularized system may result in one module which needs to be heated while another module needs to be cooled. In an alternative design it might have been possible to couple these requirements. Furthermore it is possible that two or more separately designed modules will not be correctly operable simultaneously, even though each meets its own design requirements. In this case the problem may have been caused by the original breakout of the design requirements into modular form. However, a total system test program should detect such modular interference and reject the design package. Thus such a design should never go into service, and if it does, it represents a breakdown in the specification-design-acceptance test sequence.

When additional or modified equipment becomes necessary and appropriate as a result of research and development efforts, design from scratch would require that the existing system be abandoned and a new system designed which incorporates the existing and the new technology. The degree of redesign and abandonment would, of course, depend on the complexity and overall impact of the new devices. Two noteworthy exceptions to abandon/redesign are when a new subsystem directly replaces an old subsystem or when the existing design has specifically allowed for the addition of the new equipment. However, in the ideal pursuit of the design-from-scratch approach, total redesign must be considered.

In the second design approach existing equipment is accepted as a given or base and new design needs will result in either modifying part of the existing equipment or designing new equipment which will be added to the existing configuration. This approach carries with it the necessity of interfacing the new equipment with the old. This kind of interfacing is much more likely to produce a total equipment package that is unwieldy, that approaches or exceeds overall system constraints, and that is at least partially inoperable with respect to simultaneous use of its subsystems or its use in some operational environments. However, here also an appropriate test program should prevent such designs from becoming operational.

Despite the inherent limitations in add-on design it is, of course, attractive from the viewpoints of cost and convenience. Add-on design is also consistent with ongoing research and development efforts through which new subsystems are continually evolving. When such a subsystem reaches the stage at which it should be implemented in the operational system, adding it to the existing system may appear to be more desirable than redesigning the existing system in order to accommodate the new equipment. The alternative would be either a total redesign as each new subsystem became available or the holding of new subsystems until their individual or collective importance warranted a total redesign. Under either of these alternatives actual add-ons would effectively be forbidden.

It is likely, however, that add-on design will continue to be an attractive approach and it would therefore be desirable to improve add-on design procedures in order to maximize their effectiveness.

Add-on design requires all of the predesign information outlined previously. Of particular importance is:

- Clear definition of overall system constraints and translation of these constraints into constraints on the add-on.
- Complete operational scenarios which can be used to test for equipment/equipment and/or equipment/operator interference.

Additional requirements are:

- Management structures and authority which can assure compliance with overall system requirements.
- Management structure and authority which can reject the add-on, hold the add-on, and/or declare that total redesign has become necessary.
- The cumulative effect of add-ons must be monitored so that each additional add-on can be assessed with respect to the then current system.

The appropriate management structures not only must exist as bureaucratic entities but also must be effective. Effectiveness is largely dependent on two factors: the quality of the personnel involved and the explicitness of the rules governing their activity.

It should also be noted that the simultaneous consideration of two or more add-ons can be especially dangerous with respect to correct assessment of their overall and interactive effects. Add-ons should therefore be considered sequentially. It is also appropriate to anticipate what new devices are in the research and development stream which will effect or interact with a subsystem currently ready or nearly ready for inclusion in the operational package. The opportunity may occur to combine these design projects in the final stages of their development.

Design Alternatives

We have described in general form the spectrum of information required for a system design task which includes all of the functional requirements and all of the constraints on the system. For simplicity in the following discussion it will be assumed that whether a design has achieved a function can be answered either yes or no, and perhaps more importantly whether the design has achieved all functions can also be answered yes or no. The system constraints of interest will be assumed to be in the form of limits, e.g., maximum weight. Furthermore, the operational environment and an appropriate test program will be assumed to be known.

It is recognized in engineering that there are almost always several or many alternative designs for a system. Although each design may be acceptable, the classic thought process is then one of choice between design alternatives, or in a more theoretical sense the optimization of the design with respect to one or more of the design objectives. ("Optimization" will be used here to mean "improved" or "better" as well as "optimum".) Since it is assumed here that functional achievement is a yes/no parameter, such optimization would only be amongst designs which achieve the functional requirements. Furthermore, at this point only optimization from acceptable designs will be considered; i.e., all of the candidate designs also meet all of the system constraints and are fully functional under all operating conditions.

Under these circumstances the only thing left with respect to optimization are those constraints posed in the form of a limit. For example, if system A and system B both perform the required task and the maximum weight allowed is 10 pounds and system A weighs 6 pounds while system B weighs 8 pounds, then system A is chosen under the assumption that the lowest weight system is the more desirable.

In complex designs there may be many limit-type constraint parameters, and therefore the optimization question becomes one of what to optimize with respect to--either singly or in combination. For example, if system A and system B above have respective reliabilities of .91 and .96 (compared to a minimum of .90), it is now necessary to decide if weight or reliability is the more important parameter. Adding cost, maintainability, and any number of other such parameters further complicates the decision-making process. It is recognized that optimization is most likely to involve tradeoffs since the lightest system is not necessarily going to be the most reliable, or the least expensive, or the most durable. In general, therefore, the relative importance of each parameter requires a subjective judgment. In fact, modern decision theory tends to look not for the "best" design but for the range of acceptable alternatives (and the probability of avoiding unacceptable alternatives).

INTEGRATED SYSTEMS

As discussed, the design process has been pursued to the point where choices need to be made between alternative designs so as to select that design which optimizes the adherence to system constraints, it having been assumed that we are only interested in those designs which are fully functional and within the constraint limits.

Many choices in the engineering armamentarium exist for alternative designs which would have differing weights, reliabilities, etc. Of these, the concept of interest is that of integration which will now be defined as the process of combining tasks and/or hardware so as to optimize a system design with respect to one or a combination of pre-selected constraints. Thus an integrated system will be a system in which tasks and/or hardware have been combined so as to achieve the required optimization.

Task Integration

Task integration is defined as combining or eliminating operator tasks in a man-machine system so as to, in general, simplify or combine the requirements placed on the operator such that the tasks can be achieved within the operator's short- and long-term capabilities. Tasks can be altered or eliminated by changing the hardware configuration of the system. For example, if an ejection seat release mechanism is acceptable but difficult for the operator to activate, then a hardware change which alters the location of the activator, the type of button or handle, or the force required on the activator would be considered an example of integrating the task requirement with the capabilities of the human operator. In this case optimization (or improvement) would be achieved with respect to a parametric measure of operator performance. If the activator had been inoperable in its present location, the design should be rejected. Here the design could be brought into compliance by relocating the control to a position more compatible with operator performance.

Tasks can be performed with the hands, feet, voice, body movements, eye position, and perhaps thought processes. Thus changing the body system which is used to perform a task so as to improve operator performance would also be included under task integration. In some cases multiple tasks and controls can be combined into a single device. For example, a joy stick can provide many functional inputs to the system which would otherwise require multiple body segments and hardware interfaces.

Communication from the machine to the operator can also use the traditional tactile, auditory, and visual senses as well as possibly taste and smell. Thus changing the sensory input to the operator can also improve operator performance.

The sequence and duration of tasks can be as critical as their individual performance. Thus altering when a task must be performed with respect to all other tasks will be considered a form of task integration or combination.

Unfortunately there is no simple answer to the operator input/output problem that automatically provides the optimum operator performance; however, numerous guidelines to enhancing operator performance fall under the general rubric of human factors. As in many areas of engineering endeavor, there is still much which is not known about human factors and there is considerable ongoing research to further define the enhancement of operator performance. Pending further progress in this area design alternative selection is presently limited to conformance with reasonably agreed upon guidelines and to explicit realistic testing of designs against quantifiable performance measures. Such testing is necessary to eliminate unacceptable designs as well as to choose between acceptable ones.

Hardware Integration

Hardware integration concerns the actual physical components of the system and subsystems. Here appropriate combinations can be achievable in terms of both the controls presented to the operator and the more internal parts of the system. Such combinations may serve to decrease the number of components and thereby decrease weight and improve overall system reliability. However, system reliability could also be decreased in the sense that if a multifunctional subsystem does fail, it would eliminate more functions than if a more independent subsystem failed. Thus the higher the level of combination or integration, the less chance there may be of failure but if a failure occurs, the greater would be the consequences.

Modern electronics serves to illustrate aspects of the physical integration of hardware components since one aspect of the recent history of modern electronics is that the basic building block, the chip, has become more complex with each generation such that the number of functions of a single unit have rapidly increased. The acronym VLSI as applied to current chips stands for Very Large Scale Integration. This trend and achievement represent exactly the kind of integration that is of interest here.

Given a specific set of functional requirements at any given point in time, a number of electronic components could be assembled from those available and they would be interconnected so as to achieve the desired function. Some of the components might be interconnected in a very interactive way, i.e., be part of a single circuit element which might be called a module. Other modules might also exist in which other components form the circuit. These modules could then be interconnected as necessary to achieve the whole design. In this kind of design if a new function were added to the list of requirements two approaches would be possible. One would be to add a new module that provided the new function. The second would be to add to or modify one of the existing modules, if possible, to combine the new function with the old.

True integration is achieved when the design becomes fixed and technical and economic feasibility dictate that the entire system will be replaced by only a few chips or perhaps one chip that does all of the things that the existing assemblage of components did. Such a new chip once made may be unsuitable for further add-ons, or may itself be designed such that new or altered requirements could be easily achieved without disrupting the integration. The concept, and reality, of changing a device by changing only its memory of the function to be performed, is an excellent example of integrated and yet flexible design.

In comparing the new single chip design to the old multiple component design, a number of tradeoffs may occur. The new system is undoubtedly smaller and lighter and probably consumes less power and dissipates less heat. It is, however, essentially unrepairable except by replacement, although replacement would be an easy matter. Furthermore, total system redundancy could be easily provided.

Although unrepairable, the new chip would tend to be more reliable, once past its early development, than the many components used before. However, if it failed, it is probably more likely that the entire system will malfunction whereas in the component/module design continued function of some parts of the system may be possible despite a partial failure.

The single chip may be more inflexible with respect to new requirements than the multiple component/modular device. If, in fact, new functions are necessary, the chip may have to be discarded and a new one designed. Alternately new components could be added to the master chip and a mixed design allowed to evolve. Modern electronics should serve the system designer as a model of the achievement of a very high level of integration and reliability as well. Certainly any electronic system should use this technology.

Another example of electronic integration is communications using a single channel to carry multiple signals by using different frequencies and matching encoders and decoders. This approach is also adaptable in the add-on design mode in which existing wiring is used to provide additional communication functions. In the building industry the normal electrical wiring or telephone wiring is now being used to carry energy management control signals instead of using separate wiring for the latter purpose. Here materials, labor, and some degree of complication is saved by this communications integration. However, more complex equipment is needed to produce and interpret the carrier frequencies and a failure may result in multiple systems becoming non-functional.

The achievement in integration obtained in electronic chips has not been matched in mechanical, pneumatic, or hydraulic equipment and these kinds of components have therefore become the limiting factors, with respect to size, weight, and reliability of systems. However, that is not to say that non-electronic systems cannot be physically integrated. For example, if a pneumatic control system requires a pressure source, it may be possible to design the system such that all of the control functions operate from only one pressure source. In the add-on design problem if a new control modality is required, the existing pressure source may be of adequate capacity to support the pre-existing and the new control functions, and therefore the addition of a new pressure source would not be required. If the existing pressure source was not of adequate capacity, it could be replaced by a single new pressure source of sufficient capacity to provide both the old and the new functions as opposed to adding a second pressure source to serve only the new need.

The seemingly inevitable tradeoffs again occur. The single pressure source is likely to be smaller and lighter than two pressure sources. However, if it fails, all control functions would be lost whereas if one of two pressure sources failed, only part of the control functions would be lost.

Physiological systems also provide numerous examples of physical integration in the sense that many organs exhibit multiple and, in some cases, unrelated functions. The respiratory system, for example, serves to exchange gas between the physiological system and the environment. It also serves to eliminate water vapor and as a heat exchanger. Furthermore, the respiratory system "powers" the function of speech. Likewise other organs of the physiological system have a lengthy list of functions, and in many cases there are probably additional functions which have not yet been identified.

In addition to the large number of functions of physiological organ systems, it is also noteworthy that these functions occur and are controlled at a very small size scale. The specialized collections of these small elements exhibit a combination of complex behavior in a package size which is well beyond current man-made systems. Although they may be the premier examples of integrated systems, they are none-the-less just examples. However, as examples, they may illustrate certain specific techniques for achieving sophisticated function in small packages. The concept of bionics was based on this notion that observing physiological system function would provide guidance to the designers of man-made systems with respect to methods for achieving efficient, small, and yet sophisticated and reliable system functions. Unfortunately this approach has been stymied by the incomplete knowledge of the details of physiological function and control, and relatively few man-made systems have been successfully designed by utilizing or mimicing physiological system function. However, some observations are perhaps of value as general guidance.

Higher level systems have identified subunits, each with its own structure and functions. Subunits have further subunits, and the interrelationships at these lower anatomical levels can be as complex as between the larger units themselves. These subunits have a very high degree of communication and interaction between them, and it is probable that no subunit acts totally independently of others. In some cases, there are parallel controls while in others there are series controls. In some cases, multiple path control functions are accomplished by additive effects while in others control signals are generally subtractive. Subtractive control provides a high degree of fine tuning, maintenance of homeostasis, and the potential for rapid responses. There are both local controls and system-wide controls. There are redundant systems as well as unitary ones. Despite these complex control methodologies specialization is such that some organs can be surgically replaced and the new unit can function, although perhaps not as well as the original, without the restoration of all of the normal control modalities. It is debatable whether all physiological subsystems have individually achieved optimum adaptation or if only the combination of subsystems has reached an adaptive status quo. In fact since many physiological systems are imperfect and subject to a wide array of negative external influences, it could be argued that only limited adaptation has ever been achieved. Adaptation has resulted in increased complexity and specialization of some organs, and the elimination or partial elimination of other organs and structures.

Adaptation has also been to only a more-or-less specific environment and to more-or-less specific behavior patterns. For many species, alteration in the environment or altered performance demands on the species will result in dysfunction or death.

Physiological system development has proceeded from the smallest size scale up to the organ level, and with the simultaneous integration of the organ into the total system. This presents an interesting contrast to man-made systems in which functional need is defined first. Then down-scale design defines the components necessary to achieve the function, and up-scale design defines the interfacing of the system into its surroundings. From the physiological systems perspective this represents starting the design in the middle. The achievement of comparable integration would likely require the identification of all functional requirements first so that the downscale search for design solutions can occur simultaneously and consistently with the requirements of the whole. In man-made systems the definition of a new functional requirement for an already existing system may result in the search for a way to fit it in or add it on rather that result in its integration into the design. In comparison there would not seem to be any natural examples of add-on design; instead existing systems are modified to achieve new functions. In fact, most, if not all, sudden system mutations tend to be harmful and destructive to the individual.

APPLICATION OF INTEGRATION TO LIFE SUPPORT SYSTEMS

The definition of integration given earlier is the process of combining tasks or system hardware so as to optimize a system design with respect to preselected parameters. In the case of aircrew life support systems relevant task parameters must measure the number and kinds of tasks that the aircrew member can adequately perform under actual operational conditions. System hardware integration will generally be aimed at reducing the weight and bulk of the equipment in order to reduce the burden on the operator's performance. These burdens may include fatigue, heat stress, discomfort, interference with motion, and possible risk of injury from the equipment under emergency conditions.

As noted earlier, the perceived need for integration is based on the observation that the existing systems are burdensome in a variety of ways. Important questions here are what is meant by burdensome and how did a system perceived to be burdensome become operational.

A judgment that the system is burdensome means that it either is actually unacceptable in that the functional requirements of the man-machine system are not met, or it means that the functional requirements are met, but only in some marginal way. In the latter case, dissatisfaction may imply that an alternative, although perhaps unknown, design would better meet the requirements. However, it is rarely possible to prove that the lightest, smallest, etc. design has been achieved. Rather a design has been achieved that meets the stated requirements of the lightest, smallest, etc. of several design alternatives that meet the requirements, and it has been accepted.

If the system does not meet the functional requirements, then the design process must have failed somewhere along the path from objectives to acceptance testing.

Several possibilities are:

1. The design requirements and constraints were inadequately or incorrectly stated.
2. The designers failed to recognize or meet the stated design requirements or constraints.
3. The test procedures to assure compliance with the design requirements and constraints were inadequate.
4. The new subsystem came on-line more-or-less simultaneously with other new subsystems such that the cumulative effect caused the unacceptability.
5. The burdensomeness of the system has been accepted as a tradeoff in the partial satisfaction of the requirements and/or the constraints.

If the modified system does meet the functional requirements and constraints and test procedures, then the judgment that the system is burdensome implies that the original specifications allowed a burdensome system as a solution to the problem. Thus the fault again lies with the specifications and tests for the original design.

The conclusion here is that while integration is a design objective, it does not necessarily yield unburdensome equipment and that the key to good design is the correct original specifications of the system and appropriate test and related management procedures.

RELATIONSHIP OF INTEGRATION TO PHASES OF EQUIPMENT DEVELOPMENT

A basic question posed at the inception of this project was to relate the observations made about integration to the stages of the existing research and development process. These progressive phases are 6.1 Research, 6.2 Exploratory Development, 6.3 Advanced Development, and 6.4 Engineering Development. The relevant questions are: When can integration be considered? When must integration be considered to achieve the objectives of integrated systems design? Recognizing that add-on design is likely to continue to be used, the same two questions can be asked with respect to add-on requirements.

Basic research, categorized as 6.1 Research, identifies and develops a basic knowledge base without consideration of any clear or direct application and often without including any hardware considerations. Therefore, the principles of integration and effective add-on are generally not relevant as applied to increased understanding of natural phenomena in science and engineering. An exception here would be research expressly aimed at determining exactly how a physiological subsystem achieves both its individual function and coordination with the whole.

Applied research, categorized as 6.2 Exploratory Development, attempts to explore and develop a technological base through the application of engineering principles and basic knowledge bases. This category also evaluates the practicality and feasibility of technological bases toward the solutions of specific military problems, but excludes major development. Integration principles should begin to be applied in exploratory development systems, at least at the subsystem level. The development of a sound technological base is normally initiated by the conceptual phase during which problems and needs are studied. This phase has limitations imposed by the available technical knowledge and the changing requirements which are often initially incomplete or ill defined, resulting in successive iterations. This iteration process facilitates the implementation of integration.

The potential relationship of hardware or tasks under development at this level to the existing system and its constraints needs only minimal consideration since the objective at this phase is generally demonstration of subsystem technical feasibility and the testing of concepts. However, it would not be inappropriate at this level for the investigators to be knowledgeable on the possible future relationship of their project to the whole system.

After a technological base has been achieved, projects are moved into the next phase, 6.3 Advanced Development. Within this category, technologies are combined and hardware is created for experimental or operational tests. It is at the transition from 6.2 to 6.3 and within 6.3 that integration is generally needed as part of the hardware development. In particular, the combination of technologies, either new with existing or new with new, can be achieved at this phase so that necessary future combination of equipment can be achieved at the test level. Furthermore, equipment must be configured in such a way that at least feasibility for actual future implementation can be demonstrated.

Technologies or combinations of technologies proven in 6.3 must be ultimately combined with the existing system. To achieve an adequate level of integration it would often be necessary for the entire existing system, or significant parts of it, rather than just the new technology itself, to move into the next phase, 6.4 Engineering Development, which is the last development category. Even a potential add-on component cannot proceed to 6.4 by itself since its independent further development is contrary to the goals of integrated system development.

From 6.4 systems emerge ready for service use, and generally only coarse interfacing requirements can be maintained under the concepts of configuration control and configuration management. Configuration control attempts to prevent equipment incompatibility, primarily by a codified system of check-offs and approvals, although industry bemoans excessive, unnecessary, and costly configuration control. Configuration management attempts to solve this problem by controlling and clearly defining the baseline configuration of the equipment at each stage of final development. This control makes it difficult to achieve further integration and add-on interfacing rather than integration is normally performed since integration would generally drive up the apparent cost and complexity of the subsystem project. Thus at 6.4 it is too late to achieve integration if only the new subsystem is brought into this level. Moreover, in general, a number of different subsystems may be at 6.4 simultaneously in separate projects, all of which are to be eventually interfaced with the fixed portions of the existing system.

This analysis suggests that major decision making with respect to integration of new subsystems into the existing system needs to be made between 6.3 and 6.4, since within 6.4 it is too late. These decisions begin with acceptance of the need for the technology developed in 6.3. Consideration must also be given to the relationship of this technology both functionally and structurally to existing technology, to other technology emerging from 6.3, and perhaps to promising technologies in 6.2 that would be worth waiting for. The major decision then occurs which is to select all of the system subsystems and components that will require simultaneous engineering redevelopment and to define a new project such that integration will be achieved.

In summary, integration must begin in 6.2, must be given major consideration in 6.3, and a critically important new control step is needed between 6.3 and 6.4.

RULES AND LAWS OF INTEGRATION

I. General

1. An integrated system is one in which tasks and/or system hardware have been combined so as to optimize a system design with respect to preselected parameters.

2. The critical parameters of a system and the permissible values of those parameters must be known and specified as part of the design constraints.

3. Any system, no matter how well designed and integrated, can only perform correctly under a finite set of operational conditions. Therefore the prescribed set of such conditions must be known in advance of system design and must be maintained and updated as a single source document.

4. The occurrence of new system requirements, or new useful technologies, requires the complete re-evaluation of the system definition and subsequent redesign of the system in order to maintain system performance.

5. Modularization and add-on can be the antithesis of system integration in that the resultant division of the design task reduces the opportunities to achieve the required combinations of tasks and hardware.

6. The difficulty of achieving a well-integrated system increases sharply with the number of subsystems and/or subsystem contractors and the time span over which the system is developed and used.

7. System constraints (e.g., weight) should be viewed as absolute permissible levels and alternative designs sought such that the deviation from the permissible level is maximized.

8. The word "integration" should be restricted to usage consistent with the definition given here so that the process of adding or modifying a system is not called integration if it does not meet the definition.

II. With Respect to Add-ons

1. In solving one problem through the use of added equipment, there must be assurance that the resultant new system still meets all of the previous performance and constraint requirements.

2. Every modification or addition to a system has the potential to alter the overall capabilities and limitations of the system, often detrimentally.

3. Every proposed add-on must be accompanied by an analysis of its impact on the overall system and each of its functions.

4. Whenever new requirements occur, consideration must be given to modifying the existing system, combining functions and subsystems, and deleting subsystems before proposing an add-on.

5. Addition of new functions to a system requires the existence of a comprehensive, current design and constraint specification for the as is system.

III. With Respect to Management

1. Authority must exist which can declare a system as frozen with respect to additional add-ons or modifications pending total redesign.

2. System management must control not only the existing and near-term add-ons or modifications, but also be aware of and project other developments which will affect the system in the future.

3. Development contractors must be made aware of and demonstrate understanding of the existing system and must document the projected integration of their project into the existing system.

4. Critically important management decisions must occur when useful technologies have been proven and become candidates for inclusion in the existing system.

5. Bureaucratic structures aimed at achieving system compatibility do not necessarily achieve their objective.

IV. With Respect to Life Support Equipment

1. The system must be built around the total spectrum of needs of the user and this spectrum must be known.

2. User effectiveness will depend on (1) the baseline capabilities of the user, (2) the task requirements placed on the user, (3) the environment of use, and (4) the design of the equipment being used. The first three require detailed knowledge and documentation before rational design can proceed.

3. In protecting the user from one hazard, no new unacceptable hazards should be created and no interference with other hazard preventative measures or systems should occur. Therefore a comprehensive, ongoing system safety analysis must exist.

4. A complete and up-to-date operational scenario is required to provide a test framework for the life support equipment.

5. The relative risks associated with hazards must be assessed to make inevitable trade-offs decisions between complexity and function.

INTEGRATED ENGINEERING DESIGN CHECKLIST

Do I have a clear definition of the design objectives?

Do I have a clear definition of the design task and hardware constraints?

Do I need to further understand the systems this design will interact with?

In setting tasks for the operator, do I know what other tasks the operator has and any necessary information on the ability of the operator to do the new assigned task under operational conditions?

Do the constraints provide this knowledge?

In adding hardware to the system, do I understand all the effects this hardware will have on the system and the operator?

Do the constraints provide this knowledge?

Is there available hardware in the system that can be used to achieve or partially achieve the new design objectives?

Did I use the available hardware?
If not, why?

In providing new hardware components, have I made maximum use of these components so as to avoid unnecessary hardware additions to the system?
If not, why?

CONCLUSIONS AND FURTHER RESEARCH NEEDS

The objective of this project was to identify, under the term "integration," those rules, guidelines, and management processes which when followed would result in optimal system performance and the avoidance of certain types of problems which presently exist in aircrew life support equipment. The conclusions of the analysis presented here are:

1. The occurrence of burdensome or otherwise problematical equipment is more a result of poorly defined design constraints rather than lack of integration as defined here. Therefore lack of integration is not necessarily the cause of equipment problems nor will integration necessarily eleviate them.

2. Integration, the combining of tasks or system hardware so as to optimize a system design with respect to preselected parameters, requires a detailed specification of the critical parameters and sufficient design alternatives such that the optimum design can be selected. This, in general, would require an approach in which several designs which meet the functional requirements are developed and at least conceptually tested against the constraints and parameters requiring optimization. Suitable methods or types of integration depend on the type of system being designed (e.g., electrical, mechanical, hydraulic, etc.) and the relevant design rule is simply to minimize the number and types of tasks and/or the amount of hardware necessary to achieve the functional design objectives.

3. Both technical and managerial research, development, and implementation control is necessary to (a) properly define subsystem design constraints, (b) identify existing subsystems that can or must be redesigned to accommodate other new subsystems, and (c) test any resultant system for overall compliance with total function and total constraints.

This project has identified a number of potentially useful research areas which could be pursued in order to enhance system integration achievement, in general, and specifically with respect to life support equipment. These are:

1. Continued research on the effect of equipment mounted on or worn by the user on system and user performance and the establishment of appropriate limits for tasks and equipment.

2. Development of improved design criteria for the specific area of user mounted, worn or used equipment.

3. Development of a computer-based task simulator against which new tasks can be tested for operational compatibility.

4. Development of a comprehensive operations simulator to provide a test framework for task and/or hardware additions.

5. In-depth study of existing systems to identify system configuration problems, prioritize redesign efforts and provide specific illustrations and applications of integration concepts.

6. In-depth study of the existing Air Force management structure with respect to equipment research, development, integration and configuration control to identify needed changes or effectiveness enhancement.

7. Study of the potential utility of modern decision support theory and its application to the critical technical and managerial issues in life support system design and control.

The latter is a subject which is receiving considerable attention in our Industrial Engineering Department and which has significant potential with respect to some of the identified needs.

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