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FUNCTIONAL ANALYSIS
OF
PILOT WARNING INSTRUMENT CHARACTERISTICS

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FINAL REPORT

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16. Abstract

The concept of a pilot warning instrument (PWI) is that of a relatively simple and inexpensive device which could be used to aid aviators in the visual detection and evaluation of other aircraft in their vicinity, giving the aviator ample time to select and then make an appropriate collision avoidance maneuver if necessary. Until the present study research on collision avoidance through the use of a PWI has focused primarily on hardware development.

The functional analysis of PWI systems that is presented in this report, is intended to disclose the role of the pilot in such systems and to describe the intricate relationships between the pilot, the PWI, and the operational aeronautical environment. Thirteen general functions are defined and illustrated; five performed by the PWI and eight by the pilot. The PWI functions are exemplified by references to hardware systems in use; the pilot functions are described through the use of mathematical models and empirical data.

The general functions of PWI systems are structured into three categories of Pilot-PWI systems. The major independent characteristics of these systems are then used to form system generation matrices. It is shown that over 70,000 different systems can be formed from these matrices. Recognizing the impossibility of dealing with such a number of potential PWI systems, an optimization technique and computer simulation layout are described that could be used in the selection of a limited set of optimal PWI characteristics.

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FOREWORD

This report was prepared by Rowland & Company for the Federal Aviation Administration. The work was part of a program of the Communications Development Division, Systems Research and Development Service, Washington, D.C. The work was administered under the direction of Mr. Paul M. Rich, who served as Project Manager for the Instruments and Flight Test Section, Aircraft Branch, Test and Evaluation Division, National Aviation Facilities Experimental Center, Atlantic City, New Jersey.

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LIST OF ABBREVIATIONS AND SYMBOLS

B_o	background luminance
B_{ot}	Luminance of target
CR	contrast ratio
det	detection
$\overrightarrow{E}$	visual scan axis vector
g	glimpse
h	change in altitude
N	noise
N_a	noise, air turbulence
N_i	noise, internal systems
P	probability
p	pilot
PP	Pilot-PWI
PT	Pilot-Target
R	range
$\overrightarrow{S}$	scan axis vector
$\overrightarrow{SV}$	position of target in instantaneous search volume
(t)	scan axis azimuth angle as function of time
$\overrightarrow{T}$	target position vector
Tau (τ)	ratio of target range to target range rate
v	meteorological visibility
V_a	aircraft velocity
w	wind
z	zone
ω_t	angular size of target
α	azimuth
ϕ	bank angle
ψ	change in heading
ε	elevation
θ_{mrc}	maximum rate of climb
σ_g	RMS value of wind gusts ft/sec.
ϕ_w	power spectral density of wind gusts

Pilot controls:

δ_e	elevators
δ_a	ailerons
δ_r	rudder
δ_t	throttle
δ_c	climbs
δ_d	dives
δ_{rt}	right turns
δ_{lt}	left turns

Unit vectors in curvilinear coordination system:

$\overrightarrow{i}_\alpha$	azimuth angle
$\overrightarrow{i}_\varepsilon$	elevation angle
$\overrightarrow{i}_r$	range

SECTION I

INTRODUCTION

This report is one of four reports under the same basic contract to conduct analyses of various aspects of visual separation techniques. The present study is part of a broad Federal Aviation Administration study of specific human factors problem areas which will directly or indirectly contribute to the prevention of mid-air collisions. Other issues are dealt with in other parts of the study but this particular report concentrates upon PWI systems.*

The annual toll of mid-air collisions and the high rate of near misses has prompted the Federal Aviation Administration (FAA) to sponsor research into the causes of such events and to seek means for their prevention. The frequency of reported close encounters appears to be proportional to the air traffic density.(10) This state of affairs, when coupled with the forecasted heavy increase in general aviation flying,(17) brings one to the conclusion that research and development on concepts and devices which will minimize mid-air collisions and near-misses is increasingly important.

In a great number of the reported cases of either collision or near-miss some correct action on the part of the pilot either could have prevented or did prevent a mid-air collision. However, aircraft incidents being of a somewhat sensational nature in the public mind, there has been something of a clamor for precise separation assurance and positive anti-collision avionic equipment. The unfortunate fact is that positive control is very expensive, is objectionable to a great number of aviators because of the restrictions it imposes and, furthermore, lies well beyond existing air traffic control (ATC) capability. The cost of any known contemporary airborne collision avoidance system (CAS) lies much in excess of the average general aviator's pocketbook and, in fact, is not inconsiderable to other aviation interests as well. When one considers that pilots manage to operate millions upon millions of miles under Visual Flight Rules (VFR) with relatively few incidents, one is led to the conclusion that they are already doing rather well in avoiding other aircraft and that what is needed may be simply a system to help them through their occasional lapses rather than to replace them with ATC or CAS. There is no intent to disparage ATC or CAS systems, both of which are freely recognized to have definite utility in incident reduction. However, in the interest of making its responsibilities manageable in size, Rowland & Company has been directed to continue its search in the direction of purely pilot-oriented solutions or to PWI systems.

Extensive and growing effort has been spent by the FAA and the avionics industry on research and development of a system for detecting the nearby presence of other aircraft and warning the pilot so he can spot the aircraft,

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*Rowland, G. E., and Snyder, J. F. Visual Illusion Problems. FAA Report No. FAA-RD-69-49, 1970.(39)

Rowland, G. E., and Reichwein, C. Analysis of VFR Cloud Clearance and Visibility Standards. (In preparation)(40)

Rowland, G. E., and Snyder, J. F. Aircraft Exterior Lighting and Marking. (In preparation)(41) assess its actions, and react in such a way as to avoid mid-air collision. This system concept has come to be variously known as a "Proximity," or "Pilot Warning Indicator" (or "Instrument") (PWI). It is very important for the reader to understand that as the word "PWI" is used in this report it is not really just an instrument or indicator but, instead, is a complete system involving a sensor, additional processing stages and, ultimately, a cockpit display or instrument plus a man. Collectively, the entire system is referred to herein simply as a "PWI."

By definition(11), the PWI is a device which aids the pilot in the detection and/or evaluation of threatening aircraft and allows him sufficient time to make corrective maneuvers if necessary. Full responsibility for all evaluations and decisions remains with the pilot. The PWI never maneuvers the aircraft and never replaces the pilot's eyeballs, brains, or muscles. Because the effectiveness of the PWI relies entirely on a synergistic relationship between the pilot and his equipment a meaningful analysis of desirable PWI system characteristics must, of necessity, include consideration of human factors. Such consideration has been largely lacking in prior work and is the main issue of the present study.

From the hardware viewpoint there are two general classes of PWI systems: 1) self-contained; and 2) cooperative. As the name implies, the self-contained system has all the necessary equipment for collision detection on board itself exclusively and is what is defined as a "protected" aircraft. It detects and reports upon all other aircraft ("intruder" aircraft") that come within surveillance from the protected aircraft. The cooperative system requires the use of complementary equipment on both protected and intruder aircraft. Often more information can be exchanged between aircraft using a cooperative system but each protected aircraft is only guaranteed protection against intruder aircraft using a workable and compatible system. A cooperative system never detects non-cooperative aircraft.

Another type of system called a "Collision Avoidance System" (CAS) has also been under development for some time and has been formally described in a set of specifications issued by the Air Transport Association.(2) It is very markedly different from a PWI system. This system performs all the necessary functions such that (in various versions) its output is either an indication to the pilot telling him what to do or an actual execution of an appropriate avoidance maneuver. A CAS is distinct from a PWI in that it contains integral logic which enables it to make an evaluation and maneuver decision completely on its own without an input from the pilot. The sophistication and expensiveness of a CAS is enormous compared to what is desired in a PWI. Because of its features, a CAS is presently considered economically feasible only for the larger air transports or high performance military aircraft. Most contemporary concepts for CAS are cooperative systems and provide no protection from unequipped or PWI-equipped aircraft.

The CAS systems have been mentioned here for information only and in the interest of completeness. They will not be dealt with further in this report although occasional reference will be made to them from time to time. The reader should note that both PWI's and CAS's can be either self-contained or cooperative. Examples of each class are under current development within industry. The intrinsic advantages and disadvantages to each have been discussed in a number of other places. Additional discussion of CAS is not central to the objectives of the present report.

It was one of the hopes of the technical and professional staff of the FAA that, by sponsoring the present contract on "Visual Separation Techniques," Rowland & Company would be able to develop a set of preliminary functional PWI specifications for early release to industry. In view of the fact that the specifications were to be "preliminary" and "functional" they were intended solely to express the desirable characteristics that should be sought in a PWI. The specifications would describe the desired performance characteristics but would have nothing to say about how that performance would be achieved. They were absolutely not to be interpreted as either a description or an endorsement of a particular piece of hardware or even a hardware concept, nor were they to restrict the PWI system developer to a limited or specific field of technology (radio, optics, etc.). It was felt that such attitudes, if taken by the contractor, would defeat one of the important objectives of the specifications--the stimulation of new ideas and the innovative application of growing technologies while, at the same time, staying within realistic operational circumstances.

To date, statements of PWI specifications already made by numerous aviation and pilots' organizations have ranged from purely qualitative recommendations(38, 33, 47) to the statement of specific numerical values for PWI characteristics (12, 13). Qualitatively, the general consensus is that a PWI must be low cost, self-contained, indicate at least target proximity (although other target information would be desirable), and rather easy to operate. The same agreement has not been reached on the more quantitative aspects of the specifications. Detection ranges of one mile,(13) three miles,(12) and five miles(9) have been cited as minimum detection ranges by various authoritative groups. There is no instance in which such system characteristics have ever been systematically evaluated with respect to the total environment.* Accordingly, existing specifications should be said to represent only educated guesses at the most suitable values. These various specifications are valuable and interesting but they should not be allowed to hypnotize one into believing they are necessary or true or even desirable. From the outset of the project, it was the commitment of the present effort to avoid simply stating another set of arbitrary specifications but, instead, to systematically determine an optimal set of PWI characteristics through scientific experimentation and evaluation. Thereby, fact would displace opinion and a suitable set of PWI guidelines would be obtained.

In the conduct of this study Rowland & Company has read everything it could find on the subject of PWI, has talked to representatives of many companies known to be developing PWI hardware at this time, has sat in on such of the program reviews of NASA and FAA as it was invited to attend, has held numerous technical discussions with its contract monitor, and has conceived and helped conduct several experiments. We have reached certain definite conclusions. Not all of them are diplomatic, nor will many of them be popular with either the industry or the sponsor but, in the interest of progress in PWI development, they should be stated.

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*The "environment" referred to in this report includes a great number of physical variables, operating attributes, and aeronautical characteristics such as visibility conditions, wind gusts, the target geometry, and other factors which affect the overall PWI system and are not under the direct control of the pilot.

1. Present PWI work is almost entirely oriented toward development and sale of proprietary hardware with an undesirable and largely unnecessary degree of secrecy which is impeding progress.

2. Present PWI system concepts are based more on the art of the engineering possible than on making a system that does the job better for the pilot. Expediency is the rule rather than effectiveness.

3. No contemporary system developer (either industrial or governmental) has evidence (either from paper and pencil studies, computer simulations, field trials, laboratory tests, surveys, or any other source) that his system will "work correctly" in the "aviation environment." The words "work correctly" mean reliably, repeatedly, helpfully, expeditiously, simply, and with minimum training and interpretation by real aviators with all degrees of skill and experience. The words "aviation environment" mean such things as in the pattern around an uncontrolled airport on Sunday afternoon; over water; and over tin roofs with glinty specular reflections; looking up-sun; two or three targets; one target at 1 mile and another at 10 miles almost in the same line of sight; two targets in the same "sector"; following someone down the ILS; etc.

4. There is great concern with <u>sensing</u> the intruder aircraft and with signal manipulation, and almost no concern whatsoever with how to tell the pilot of the protected aircraft where to look. There is, in short, almost no concern with <u>display</u> of the data. Display of the data is where it all pays off. It does absolutely no good to sense something unless the pilot is helped into doing the correct thing about this information.

5. The solution of a PWI is being sought exclusively in the hardware aspects with almost no attempts whatsoever to interact with or to utilize the software aspects of human capabilities and limitations of the ultimate user. In view of the extraordinary abilities of the human as sensor, processor, logician, etc., this human (software) contribution to PWI systems must not be abandoned for a purely electronic solution to collision prevention. The PWI development process(not "program," for that would imply that it was organized and it is not) seems to be a case of engineers designing and building something based on pure technology and then trying to put it on the market. This is precisely backwards from the way equipment should be developed. To be truly successful the user's requirements, capabilities and limitations, and the operational circumstances should all be laid out in advance. Then, and only then, should the designer begin to design hardware.

The FAA, through its personnel in Communications Development Division, Systems Research and Development Service in Washington, D.C., and the Aircraft Branch, Test and Evaluation Division, National Aviation Facilities Experimental Center in Atlantic City, N.J., has had the wisdom to call the whole PWI process into question. Rowland & Company has been directed to take a "pilot-first" attitude in the research reported herein rather than an "equipment-first" attitude. The results, however, have not been as satisfactory as originally anticipated. It has been found that not nearly enough is known about the human as pilot to design a satisfactory PWI for him. As a result it has been necessary to resort to the next best thing.

This report describes the research plan that should be followed in order to obtain the necessary information.

One of the basic problems of PWI development is that a fundamental keystone of system development has not been laid. There does not appear to have been a functional analysis of the PWI system as a totality. The present study has carried out the initial portions of this analysis and points the way for the remaining analysis to be done.

Functional analysis is the process whereby a system is analyzed by delineating the specific functional tasks performed by elements of the system and describing the interrelations of these functions within the system.

A functional analysis of PWI systems has been undertaken in this study for several reasons:

a. As mentioned above, functional analysis is required in order to achieve one of the final products of this project, the specification of all the major characteristics of a PWI system.

b. By performing a functional analysis one is forced to recognize, define, and analyze the implicit and explicit tasks of individual components of the total system and to determine the completeness of the empirical data which describe these tasks.

c. Attention is focused on those tasks or functions required both of the pilot and of the PWI hardware components to complement each other in the PWI system under investigation.

d. The logical interplay between the PWI, the pilot, and the environment can be studied.

e. The effect of variations in pilot performance or capability on the operation of the complete system can be analyzed specifically.

f. A functional analysis lays the groundwork for a computer simulation of the entire system and the subsequent parametric analysis of system performance.

For the present case, the system functions can be divided into two general categories; those performed by the pilot, and those performed by the PWI. The interaction of functions from one category with those of the other form the man-machine interface.

The identification and selection of system functions can be carried out at any of several degrees of specificity or generality. The choice of level depends on the desired degree of detail, the aspects of performance to be studied, and the critical decision points of interest in the system. It should be understood, therefore, that the functions described in this study serve only the intent and purpose of the present research and are in no way purported to be a universal set of PWI system functions. The functions selected and defined in the following section have rather broad-based meaning attached to them in order to preserve the generality of this study and to avoid making an analysis having relevance only to a PWI system having a particular design or principle. As a result, particular attention must be paid to the functional description of each function rather than to the name assigned to it. It is well recognized that a study that cuts across several technical disciplines suffers the possibility of creating semantic problems in its terminology. To minimize these problems particular attention has been paid to the definition of functional terms in the following section of this report.

The functions ascribed to the PWI itself were selected to focus on some of the more obvious characteristics, namely; range, resolution, target selectivity, information content, and pilot-PWI interfacing.

While the desired end product of this program is the specification of numerical values for these characteristics, the seemingly more circuitous route of defining PWI functions from these characteristics aids in conceptualizing further system characteristics and organizes the interactions of these characteristics with the pilot and the environment.

As shown in Figure 1, there are three aspects to each PWI function: 1) the inputs on which the function acts; 2) the functional process itself; and 3) the outputs of the function. The inputs and outputs are largely prescribed by the morphology of the system under review. The inputs to each PWI system function are sometimes derived from the environment, sometimes from other PWI functions, and sometimes the result of pilot functions.

The PWI functional processes, in some instances, work so as to idealize a data transformation process. That is, certain input data may be transformed, filtered, stored, retrieved, or categorized, etc., by some completely deterministic process. On the other hand, some PWI functional processes are best described stochastically whereupon the function outputs are statistically distributed with respect to the inputs.

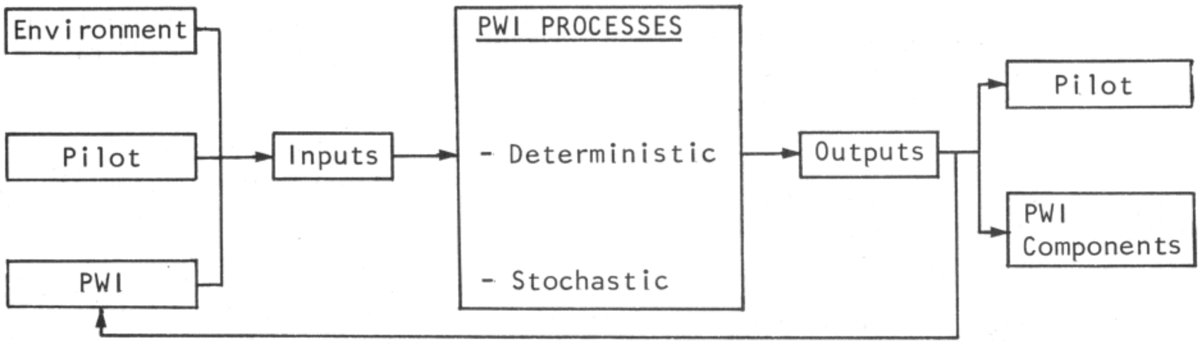


Figure 1. Generalized PWI Function

The development of comprehensive pilot functions requires a similar approach to that taken in the development of PWI functions. Perhaps because pilots are not designed on drawing boards and do not possess the uniformity and predictability of machines, descriptions of pilot functions have been largely ignored in previous efforts to model the PWI system. The realization of the crucial role of the pilot in this system, however, leads one to recognize the absolute necessity for fulfilling this lack by describing and analyzing the functions performed by the pilot.

The pilot's essential role in the system is established by the very ground rules of the PWI concept. By definition, a PWI can only aid the pilot in his detection and evaluation task; it cannot completely evaluate a threat or maneuver the plane. These tasks are solely the responsibility of the pilot.

If system performance is to be measured by the number of successful collision avoidances, it is the pilot who plays the dominant role in determining the performance of the system. The pilot's perceptions, interpretations, decisions, and reactions are the essential factors in the total system performance. Number and accuracy of detections by the PWI have usually been taken as a measure of the worth of a PWI system but, as is seen here, that is only a part, perhaps even a trivial part, of the real performance of a PWI system.

With this in mind, the pilot functions in the analysis herein were selected to emphasize human perceptual abilities, allow for the variability of human interpretations, elucidate human decision criteria, and integrate human reaction times into the total PWI system. This has proven to be very difficult to do and is probably one good reason why previous PWI system models have largely skipped lightly over the pilot.

The structure of a pilot function is similar to that of a PWI function. In Figure 2, the inputs to the pilot function characterize the information that comes to the pilot from the environment, the aircraft, the PWI, or other pilot

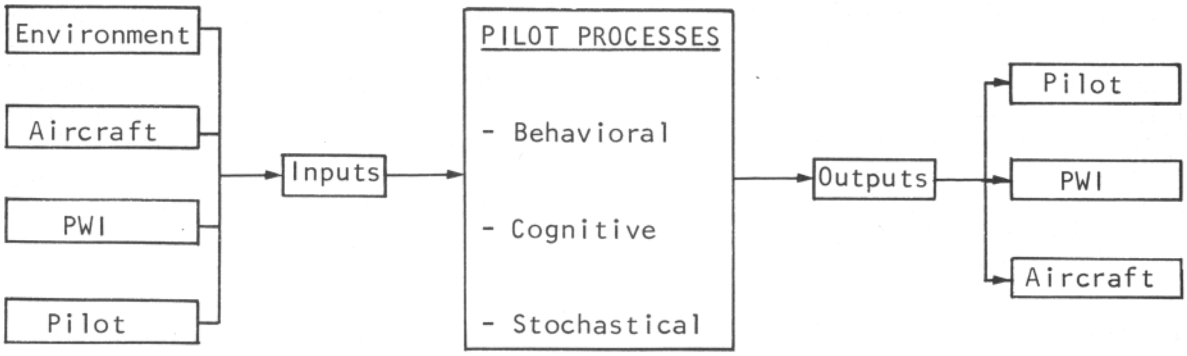


Figure 2. Generalized Pilot Function

functions. The exact number and origin of these inputs are determined by the system structure. The pilot function outputs are limited to bits of information which go to other pilot functions and pilot actions which, in turn, act as inputs to the PWI or the aircraft.

The processes involved in pilot functions are generally of three types: behavioral; cognitive; and stochastical. Behavioral processes form direct stimulus-response links as in learned or instinctive reactions. Cognitive processes allow the pilot to reach conclusions based on information perceived through his senses or stored in his memory. Stochastic processes handle most of the interface information traffic betweeen the pilot and either the PWI or the environment. A specific pilot function may include one or any combination of these three processes.

As is the case with all psychological phenomena, the pathways between one pilot function and another pilot function consist of intervening variables not subject to direct observation. The only extrinsic or measurable relationships that exist with regard to pilot functions are those between the pilot and the aircraft or the PWI. The fact that the relationships between pilot functions are inferred, not overtly visible and objective, raises an important point. Since such relations are not directly measurable the relationship itself is inferentially obtained and difficult to "prove" definitely. This is also the case in the relation between the pilot's perception of information from the target and his evaluation of the target as a threat. In the real world, the information a pilot uses and the way he uses it is, practically speaking, very difficult to know. However, careful experiments that systematically control the information available to the pilot and measure his response will allow objective inferences to be made concerning the intervening variables which guide the pilot's behavior. It is a challenge to the experimentalist to design a set of experiments that will accomplish this objective. In the meantime, the supposition of logical functions and relations between these functions will permit this present analysis to continue and will aid in formulating the hypotheses to be tested by experimentation.

From another viewpoint, system design will benefit substantially if models are built including hypothetical characteristics of pilot functions to determine what a pilot should be doing rather than trying only to model what he has been doing. The analytical assessment of visual search and evaluation techniques, for example, and the determination of the relative merits of each of several techniques would strengthen the foundations of a comprehensive pilot training program through bringing about the utilization of the best of these techniques. This principle of modeling hypothetical characteristics as a general program of PWI modeling through simulation is put to good use, as described elsewhere in this report.

At this point it is evident that two classes of functions have been presented in very broad outline; pilot functions and PWI functions. These are the fundamental man/machine functions out of which the successful airborne system must be made. It is now appropriate to attempt to make a further breakdown of these broad classes into more specific sub-functions.

In the section following, the general functions common to all PWI systems are identified, defined, and illustrated in block diagrams. A series of PWI systems is generated by varying the structural relationships between the individual functions and altering the characteristics of the functions themselves. Finally, the general layout of a computer simulation and the results it would produce are discussed. Thus, inductively generated functions would be reduced to realistically tested and evaluated specifications that would provide necessary and sufficient guidance in PWI development activities.

The question may be asked, what happened to the set of functional specifications the contractor was to supply. The answer is that it has not been possible to generate a defensible set of specifications. A variety of simulation and experimentation jobs would have to be done before a valid set of specifications could be produced. Why this is so and what can be done about moving toward those specifications, will be evident in the further content of this report.

SECTION II

FUNCTIONAL ANALYSIS

Using the general approach outlined at the end of the preceding section, a set of general functions has been formulated to cover, in the broadest possible sense, any conceivable PWI system. These functions include the tasks of both the pilot and the PWI since both are considered elements in what is referred to here as a PWI system. These functions are defined and illustrated in this section of the report. The definitions given and the illustrations used reflect much of the past thought along the lines of PWI systems; however, they should be given a liberal interpretation and be allowed to act as an incentive for new ideas rather than simply as a framework for restructuring old ones.

The PWI functions, the machine part of a PWI system, are generally illustrated in the following discussion by examples of possible or existing PWI characteristics pertinent to that particular function. In most cases, only the more commonly known examples are cited for clarification of the function's definition. In the case of pilot functions, the human part of a PWI system, experimental evidence, when available, is used to describe the characteristics of the pilot functions. Rather than have a separate section of the report for the literature review, discussions of the relevant technical literature are given in text wherever they are considered most pertinent. Mathematical models or distribution curves of experimental results are used to quantify these descriptions as much as is possible at this stage of the PWI system development art.

In order to provide an overview of the various activities, decisions, and actions which occupy the PWI hardware or the pilot during aviation operations a schematic block diagram of the general overall process is presented as Figure 3. It will be seen therein that a number of circumstances can be described. For example, the PWI hardware can detect a target, inform the pilot, the pilot can look where the PWI display tells him to look; the pilot sees the target, decides it is a hazard, and maneuvers the aircraft. On the other hand, the pilot could detect the aircraft before the PWI device (assume range limitation, unreliability, skipped scan, etc.,) whereupon he might look at the PWI display, not see any evidence of a target, conclude the PWI was not working correctly, and react by re-adjusting the PWI hardware controls to improve the electromechanical behavior of the set; meanwhile using human eyeball/brain/muscle as his see-and-avoid system. Close examination of Figure 3 will reveal a number of inner loop and outer loop subsystems that form parts of the total man/machine functions, depicted here as a PWI system.

In this report will be found discussions of the major functions which shape, condition, and control the output of the total system. Some of these functions are accomplished by electromechanical parts of the system and other functions are executed by the pilot part of the system. A number of the functions shown in Figure 3 will be discussed first.

The format used in naming functions prefixes the function with "PWI" or "PILOT" to characterize whether they are performed by the machine or the man respectively. Table 1 lists the general functions by prefix groups.

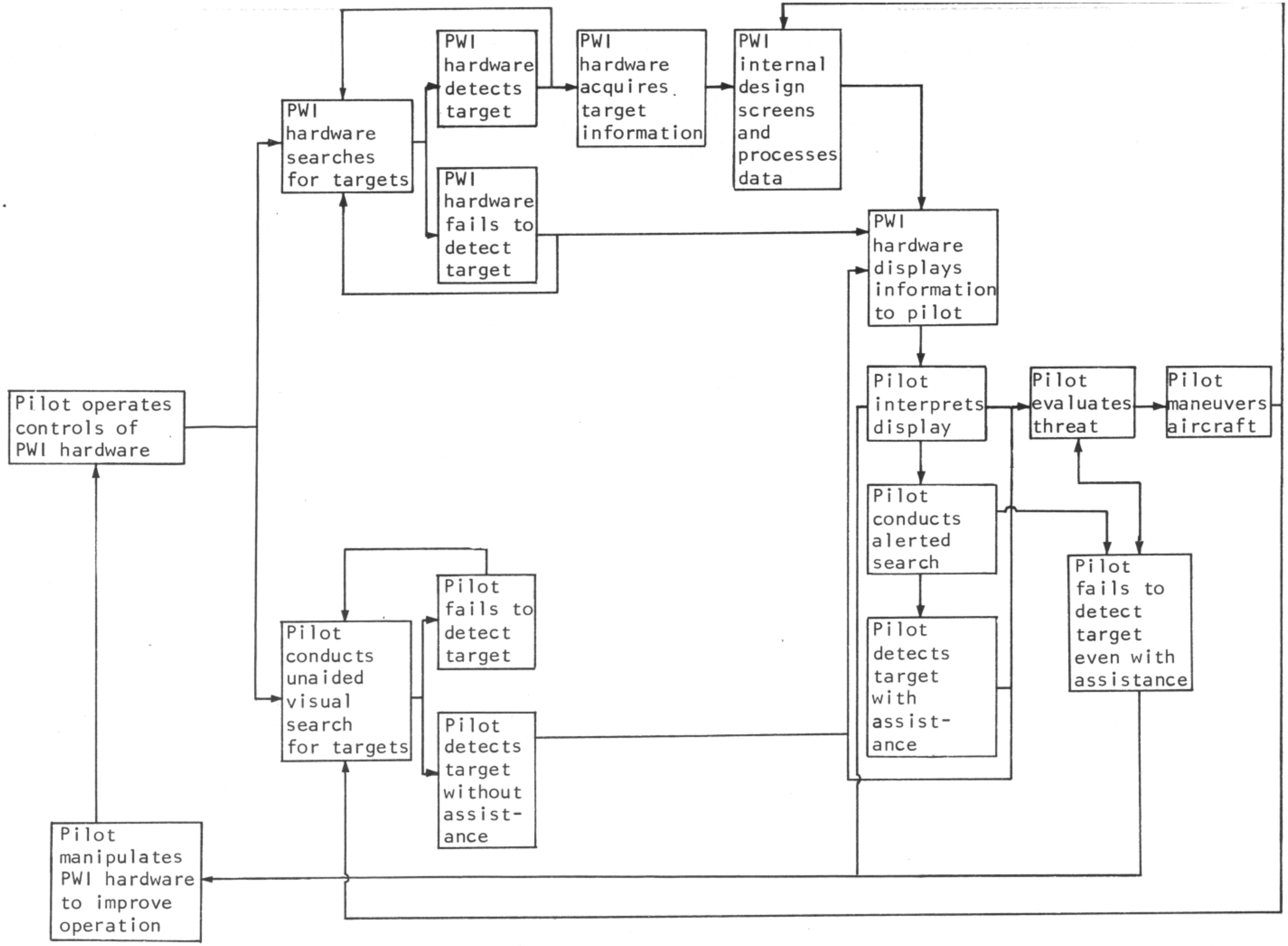


Figure 3. Flow Diagram of Functions in PWI System

TABLE 1. GENERAL PWI-PILOT FUNCTIONS

PWI Functions (Machine functions)	Pilot Functions (Man functions)
PWI SEARCH	PILOT-PWI CONTROL
PWI DETECTION	PILOT SEARCH
PWI DATA ACQUISITION	PILOT ALERTED SEARCH
PWI SCREENING	PILOT DETECTION
PWI DISPLAY	PILOT TARGET INTERPRETATION
	PILOT-PWI INTERPRETATION
	PILOT THREAT EVALUATION
	PILOT MANEUVER

A. PWI FUNCTIONS (Machine Functions)

1. PWI Search Function

This function describes the manner in which the PWI system searches for targets in the volume surrounding the protected aircraft. The output of this function is the axial position of the scan volume, the specific volume under scrutiny at a given instant of time. The position of the scan volume may be fixed with respect to the entire search field (42) or it may sweep through all portions of the search field as could the search beam of an IR scanning system.(1)

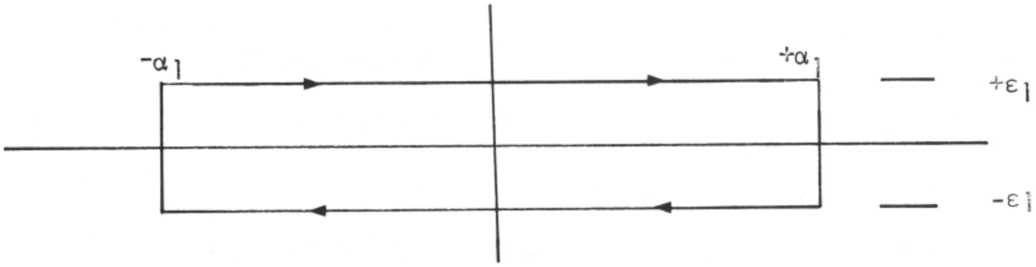
The function is semi-autonomous; that is, it may generate an output, the scan axis vector, without requiring an input from another function. Typically, though not necessarily, scanning sensors are preprogrammed to slew from side to side in an oscillatory fashion. One possible technique is to slew from left to right at a positive elevation angle then return right to left at a negative elevation angle as illustrated in Figure 4a. A system developed by Sperry Gyroscope Company (22) uses a full 360° scan at 30 rpm as shown in Figure 4b.

Mathematically, the scan axis will be denoted here by the vector:

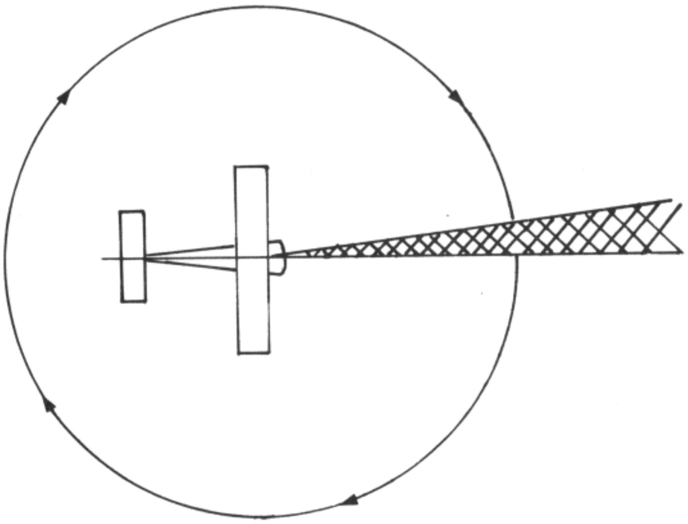
$$\vec{S} = \alpha_s(t)\ \vec{i}_\alpha + \varepsilon_s(t)\vec{i}_\varepsilon \tag{1}$$

where $\vec{i}_\alpha$ and $\vec{i}_\varepsilon$ are unit vectors in the curvilinear coordinate system of azimuth and elevation angles respectively. Strictly speaking, they should be referenced to the pivot point of the sensor, however, considering the distances to the targets involved here, they will be referenced to the origin of the aircraft axes as shown in Figure 4c. (t) is the scan axis azimuth angle as a function of time. As an example, for the scan pattern shown in Figure 4a:

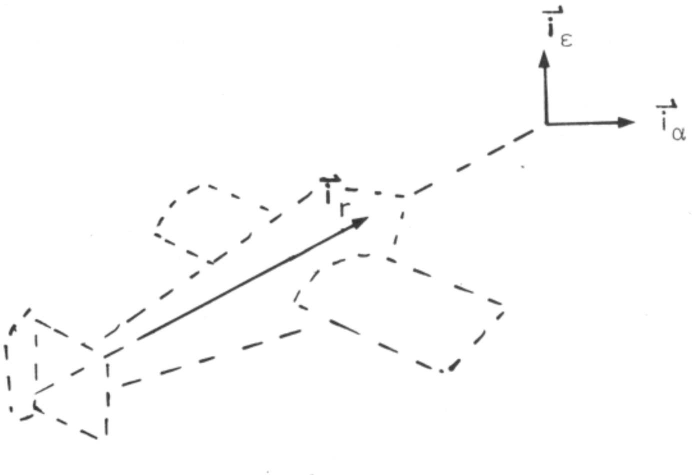
$$\alpha_s(t) = \alpha, \sin wt \tag{2}$$



(a) Rectangular scan pattern



(b) Rotating scan



(c) $\vec{i}_r$, $\vec{i}_\varepsilon$, $\vec{i}_\alpha$ coordinate system

Figure 4. PWI Scan Patterns and Spherical Coordinate System

$$(3) \qquad \varepsilon_s(t) = \begin{cases} +\varepsilon, \text{ for } \cos wt > 0 \\ -\varepsilon, \text{ for } \cos wt < 0. \end{cases}$$

The scanning process is called semi-autonomous to allow for the possibility of controlling the function output, the scan vector, by using overriding commands from other PWI functions or from the pilot. One example of this would be the use of a target detection signal to freeze the scan vector on the target thereby decreasing the likelihood of losing the target on a consecutive sweep. A further example of an input may be an action which comes from the pilot who wishes to match the sensitivity of the scan with the environmental conditions at hand. For example, a pilot is operating a very fast aircraft which is making a rapid letdown. He might wish to concentrate the energies available to him by scanning predominantly in a forward and downward direction since threats from other directions would be less likely to be hazardous. These inputs and a general diagram of the PWI SEARCH function are shown in Figure 5.

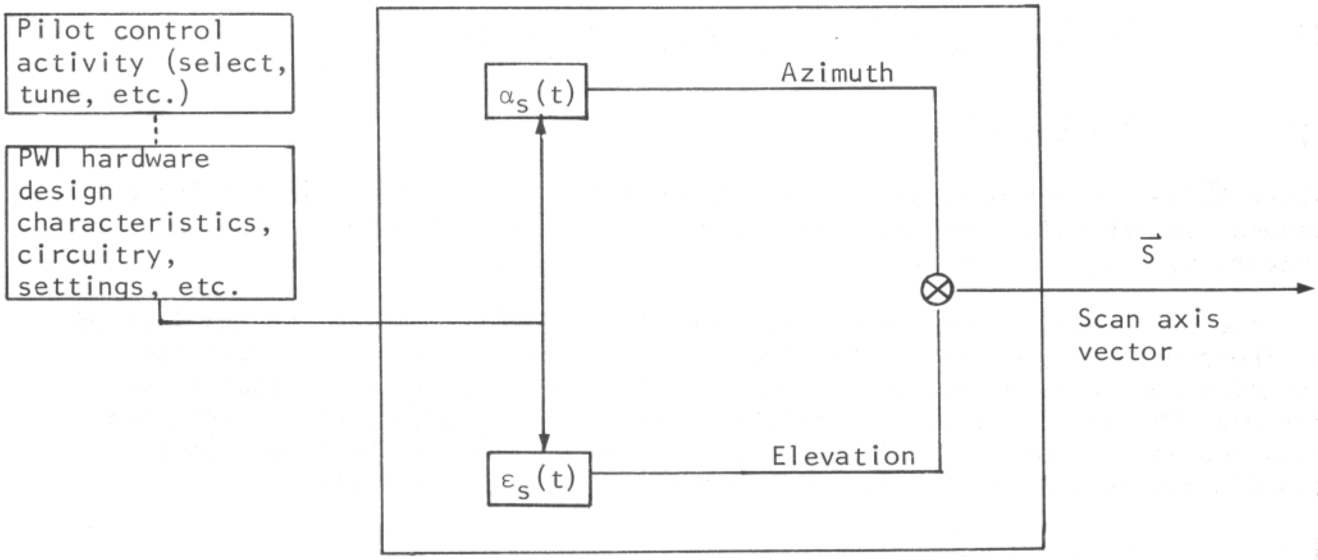


Figure 5. PWI SEARCH Function

2. PWI DETECTION Function

Detection is defined here as the recognition of the presence of a signal representing an airborne target against a background of environmental noise. For example, in self-contained PWI systems it could be the recognition of a radar echo or the detection of an IR source. In cooperative systems it could be the reception of a transponder response or the detection of a coded rf signal. Using whatever techniques are made available by present or future technologies, this function embodies the concept of perceiving the existence of a target within the airspace surrounding the protected aircraft.

In the structure of the PWI DETECTION function, as illustrated in Figure 6, two inputs are required; one the scan axis vector, $\vec{S}$; the other, an input from the environment, is the target position vector, $\vec{T}$, accompanied by the angular size of the target, ω_t. The target inputs are for computational use only in this analysis. The fact that they are fed into this function does not imply that they would be used per se in an actual PWI sensor. $\vec{S}$ is a two-dimensional vector while $\vec{T}$ is three dimensional:

$$\vec{T} = \alpha_t(t)\vec{i}_\alpha + \varepsilon_t(t)\vec{i}_\varepsilon + R_t(t)\vec{i}_r \tag{4}$$

where $\alpha_t(t)$, $\varepsilon_t(t)$, and $R_t(t)$ are the instantaneous azimuth, elevation, and range measurements of the target with respect to the protected aircraft body axes as shown in Figure 4d. The subtraction of $\vec{S}$ from $\vec{T}$ is accomplished in the following sense:

$$\vec{T} - \vec{S} = [\alpha_t(t) - \alpha_s(t)]\ \vec{i}_\alpha + [\varepsilon_t(t) - \varepsilon_s(t)]\ \vec{i}_\varepsilon + R_t(t)\vec{i}_r \tag{5}$$

$$\vec{T} - \vec{S} = \theta_{sv}(t)\vec{i}_\alpha + \phi_{sv}(t)\vec{i}_\varepsilon + R_{sv}(t)\vec{i}_r \tag{6}$$

$$\vec{T} - \vec{S} = \overrightarrow{SV} \tag{7}$$

where $\overrightarrow{SV}$ is the vector representing the position of the target in the instantaneous search volume expressed in terms of the polar coordinates of the search volume, θ_{sv}, ϕ_{sv}, and R_{sv}.

The major system characteristics specified in this function are manifested in the probability of detection function, P_{det}, which essentially describes the size and shape of the search volume surrounding the system's scan axis. For most PWI systems this probability function can be adequately represented by a four-dimensional distribution function consisting of the three space coordinates in the vector $\overrightarrow{SV}$, and the angular size of the target:

$$P_{det} = P\ (\overrightarrow{SV},\ \omega_t) \tag{8}$$

where ω_t refers to the apparent angular size of the target with respect to the PWI sensor. Depending on the operating principle of the system in use, P_{det} may be affected by such environmental conditions as atmospheric attenuation of the sensed signal ground clutter, and internal noise in the sensor itself. Unfortunately, experimental data on the effects of these phenomena upon PWI components are not always available nor necessarily directly applicable. However, there is reason to hope that approximations based on theoretical considerations may be used, as they have been used successfully in the evaluation of sensor techniques as applied to CAS analyses.(27)

Quite often the detection probability is not expressed in ideal form as the cumulative probability of detection when the target flies further into the search volume. Instead, a sharp boundary is sometimes defined in which the probability of detection jumps from 0 to 1 as a target enters the search volume. This simplifying assumption greatly reduces the compexity of the

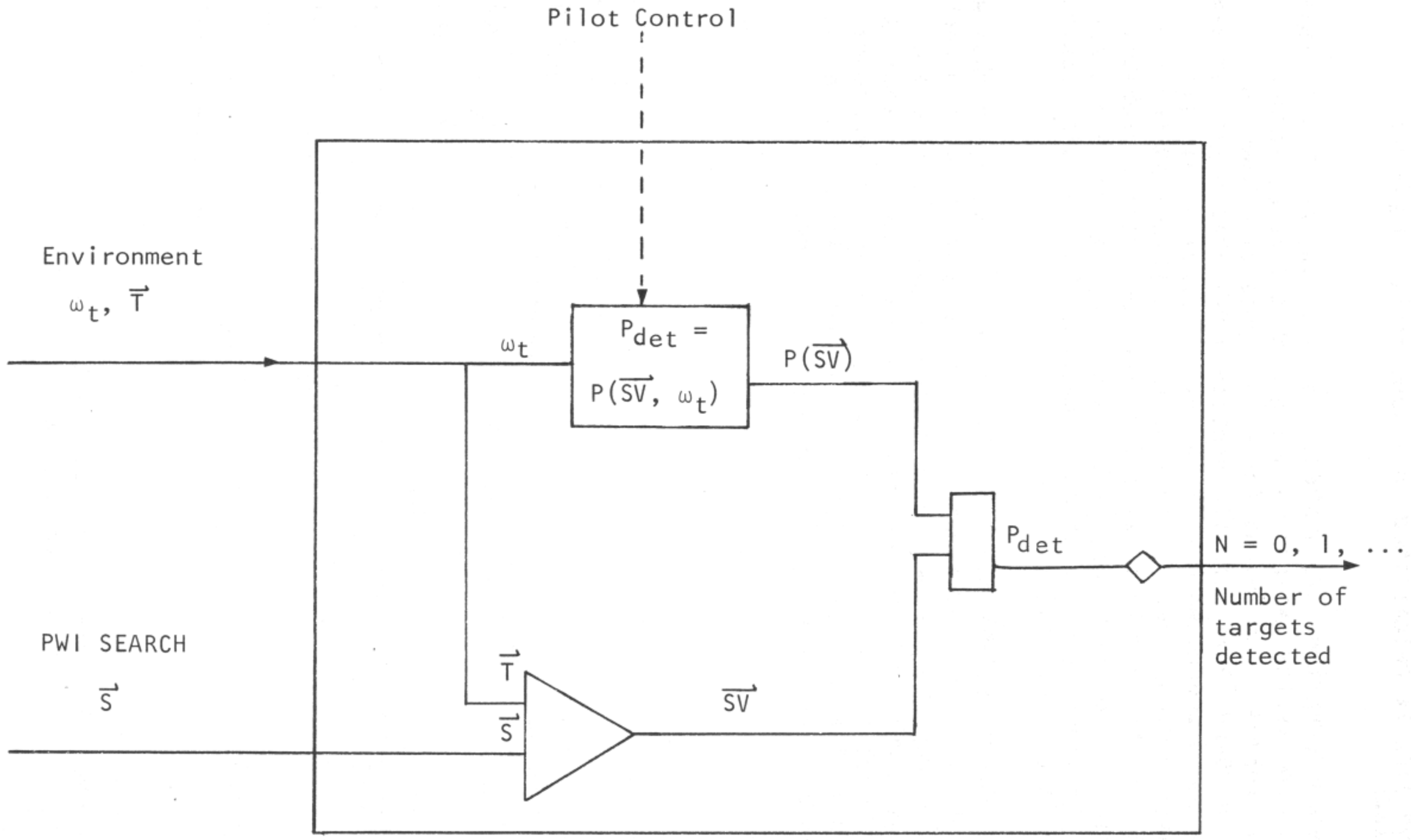


Figure 6. PWI DETECTION Function

analysis without appreciably altering the overall results, particularly if the boundary is chosen conservatively. An example of this is shown in Figure 7. Here the boundaries are outlined from empirical data on the points at which a communication link is established in a cooperative interrogator-transponder system.(22)

As with the previous function, PWI SEARCH, the pilot may be able to exercise his judgment in some system designs by doing such things as adjusting the range of the scan volume. Provisions for such inputs are shown in Figure 6. With the increase in air traffic density a PWI system with an extensive search field would undoubtedly find several aircraft within its search volume on numerous occasions. As part of the PWI DETECTION function then, one would also wish to be able to stipulate the conditional probability of detecting secondary and tertiary targets given that a primary target has been detected. Few contemporary PWI concepts appear to handle this requirement very well if, indeed, they handle it at all.

The output of the PWI DETECTION function is simply the indication that a target has been detected. As mentioned earlier, this output may be fed back to the scan control to stop the scan and lock on the target. There are a number of other things a PWI could be designed to do, based upon whether it detects or does not detect. However, aside from determining the existence of a target the PWI DETECTION function offers no further information on the target. This task is assigned to the function next described.

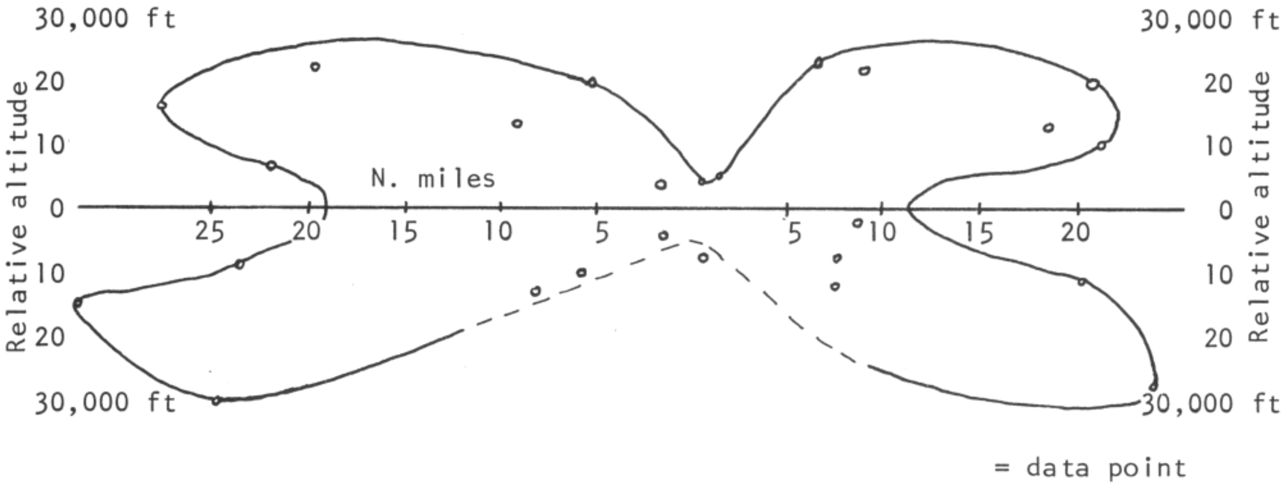


Figure 7. Possible PWI DETECTION Zone
(From reference 44)

3. PWI DATA ACQUISITION Function

Once having detected a target, the PWI mechanism next extracts such data from the target as is commensurate with the system characteristics and capabilities. The data may be derived by the PWI mechanism itself as in a self-contained system, or it may be transmitted by the target as in a cooperative system. The advantage of one technique is the disadvantage of the other. Generally, more accurate information on target altitude, heading, and possibly trend or intent, can be obtained through the transmission of coded information in cooperative systems, however, the target must possess compatible transponding equipment. A self-contained system frequently suffers from measurement inaccuracies due to environmental turbulence or other noise sources; however, it is equally applicable to all target aircraft. Indeed, this dilemma alone has been the focal point of 90% of the debate on what type of system should be used.

The PWI DATA ACQUISITION function contributes heavily to expanding the complexity and cost of the system; therefore, the ultimate value of obtaining a particular form of data to a given degree of accuracy must be carefully evaluated.

This function has both deterministic and stochastic properties. The target data is generated by decoding the target inputs to this function directly or by computing the data from internal inputs, namely, inputs from the PWI SEARCH and PWI DETECTION functions. In this analysis, however, the true target data are used as inputs to this function and at the function outputs are the target data as received and interpreted by the PWI.

Since this function is concerned with the transmission and processing of information, noise is an inherent feature of the system characteristics. Noise may enter this function on the inputs, during the processing, or during generation of the outputs. For the purposes of this analysis, all noise inputs have been lumped together into two sources: air turbulence noise, N_a; and internal system noise, N_i.

Air turbulence noise, N_a, represents the random motion of both the target aircraft and the protected aircraft as a result of atmospheric activity such as boil, refraction, and wind gusts. The noise is added to the true target variables as they enter the PWI DATA ACQUISITION function, as shown in Figure 8. The effect of N_a on the target variable depends on the type of aircraft involved and the nature of the variable.(32) For example, the power spectral density of wind gusts, ϕ_W, has been empirically found(36) to be:

$$(9) \qquad \frac{\phi_w(\Omega)}{\sigma_g^2} \qquad \frac{10^3\ (1 + 3\times10^6\ \Omega^2)}{\pi\ (1 + 10^6\ 2\ )^2}$$

where $\Omega = \frac{w}{V_a}$, the frequency of the gusts in radians/sec. normalized by the aircraft velocity, V_a, and σ_g is the RMS value of the wind gusts in ft/sec. σ_g, for a given altitude and wind condition, can be found in Table 2.

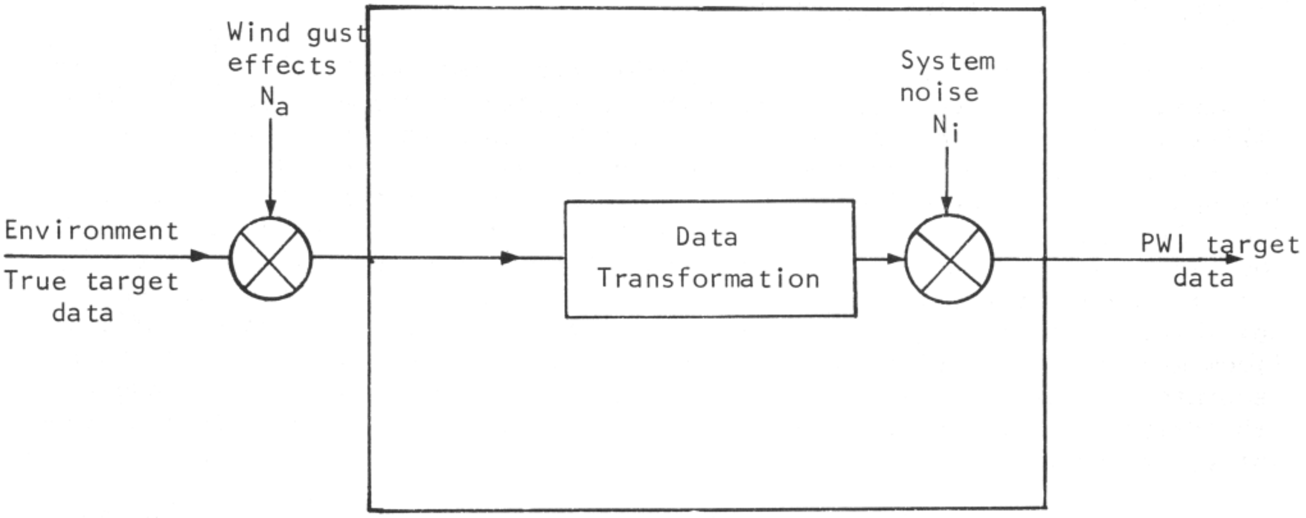


Figure 8. PWI DATA ACQUISITION Function

TABLE 2. MAXIMUM VALUE OF σ_g IN FEET/SEC FOR 50% OF THE TIME (FIRST VALUE); FOR 99% OF THE TIME (SECOND VALUE)

	Altitude (feet)		
	0 - 10K	10K - 30K	30K - 50K
Calm	1 ft/sec, 7 ft/sec	.4 ft/sec, 4.5 ft/sec	.4 ft/sec, 3.5 ft/sec
Clear air turbulence		2 ft/sec, 8 ft/sec	
Cumulus clouds		4 ft/sec, 16 ft/sec	
Thunder-storm		7 ft/sec, 26/ft sec	

The power spectral density is essentially the same in all directions, therefore, the power spectral density of N_a, the random motion of the aircraft, is simply:

$$\phi_{N_a}(\Omega) = \left|H(\Omega)\right|^2 \phi_w(\Omega) \quad (10)$$

where $H(\Omega)$ is the transfer function relating wind gusts to the particular aircraft parameter of interest.

The second source of noise, internal noise, is defined here as that noise which appears on the output of this function, PWI DATA ACQUISITION, and is not attributable to the atmospheric noise, N_a, associated with the input. This noise is electrical, optical, or mechnical in origin and is characteristically associated with the technique used by the PWI to acquire the target data. In this analysis, however, the specific sources of N_i such as background noise, oscillator drift, power supply fluctuations, etc., are presumed to be controllable and therefore are not as important as the statistical description of the noise that appears on the functional outuut of PWI DATA ACQUISITION, for it is only the effect of N_a and N_i on the following PWI functions that is of interest to this analysis.

As examples of typical target parameters that might be determined by the PWI DATA ACQUISITION function the following were once cited (37) as target parameters important to the pilot. (Table 3.)

TABLE 3. TARGET PARAMETERS OF IMPORTANCE TO THE PILOT
(from Reference 37)

PRESENCE	RELATIVE ALTITUDE	HEADING
POSITION	COURSE	AIRSPEED
IDENTIFICATION	RANGE	RANGE RATE
ATTITUDE	INTENDED MANEUVER	

Of these parameters (Table 3) the determination of target presence has already been assigned to the PWI DETECTION function; the remainder, however, are valid candidates for the PWI DATA ACQUISITION process.

Target position in terms of relative bearing and elevation has been obtained in actual systems by alternately determining the position of the scan axis at the time a detection occurs (31) or, as in the case of one type of IR system, directly reading the X - Y position of the IR image of the target on a silicon detector.(30)

The remaining variables are most readily and accurately determined by what are generally considered cooperative systems at the present state-of-the-art. Certainly identification (i.e., aircraft type), attitude, and intended maneuver are predisposed to the use of a cooperative type of system by their very nature alone. The use of altitude coded signal formats have allowed aircraft using compatible systems to transfer altitude information and make relative altitude comparisons.(16, 35) This particular information, relative altitude, is extremely valuable in reducing the number of detected targets requiring further threat evaluation. Range and range rate measurements have been successfully obtained in cooperative systems (5, 22) by measuring the time delay between the transmission of an interrogation pulse and the reception of a transponder's reply.

The fact that self-contained systems have not, as yet, fared well in successfully measuring the target parameters listed in Table 3 is not necessarily a reflection on the technique itself, but rather on the state of development of self-contained systems technology. Self-contained systems are preferred by general aviation organizations primarily because of the universal applications of such systems. This will always remain a valuable asset of self-contained systems and may eventually outweigh the majority of their disadvantages.

4. PWI SCREENING Function

The references which have been made to invocation of pilot inputs to control the range and thresholds of the previously described functions imply the existence of a filtering or screening capability in the system to reduce unnecessary alarms. The shape of the search field, as an example, is in itself a screening process. An extension of this process may also be made to take place automatically in the PWI itself. Hence, the PWI SCREENING function is defined as including any filtering, selection, or screening processes within the PWI itself that are deliberately aimed at reducing the number of detected targets to those only of concern to the pilot, and thereby reducing the false threat alarm rate.

Considerable attention has been paid to this function in CAS research; for the CAS carries this process to the full extreme of complete threat evaluation. The techniques and findings that have evolved from CAS studies (24), particularly those investigating the CAS threat evaluation logic, are extendable to similar areas of PWI research.

One relatively common technique used in the CAS logic, for example, is the relative altitude gate, ΔZ. To be evaluated further as a threat, a target's projected relative altitude with respect to the protected aircraft must fall within a preset value, ±500 feet, for example. Using the projected relative altitude not only accounts for those aircraft that are about to desdend or climb into the co-altitude zone at some time in the near future, but also eliminates those aircraft that are presently co-altitude but will be out of the co-altitude zone before any hazardous situation arises. While projected co-altitude calculations may be beyond the scope of a PWI system, the use of a co-altitude gate alone is not. The use of altitude coding techniques in this respect has already been mentioned.

A further widely used CAS threat evaluation technique is based on the ratio of target range to target closing range rate, τ (tau). This ratio, in unaccelerated flight, is the time left until collision or closest approach, whichever is the case. It has proven to be effective (24) in discriminating threat conditions and even works to some extent during turning maneuvers. (46) A complete evaluation and maneuver logic has been built around τ thresholds in the design of a CAS; in the less sophisticated PWI, a single τ threshold might serve a good purpose as an elementary target screening test.

A general schematic view of the PWI SCREENING function is provided in Figure 9. The inputs come directly from the PWI DATA ACQUISITION function and the functional processes within the function consist of the screening criteria. The output of this function is the restatement of the target data

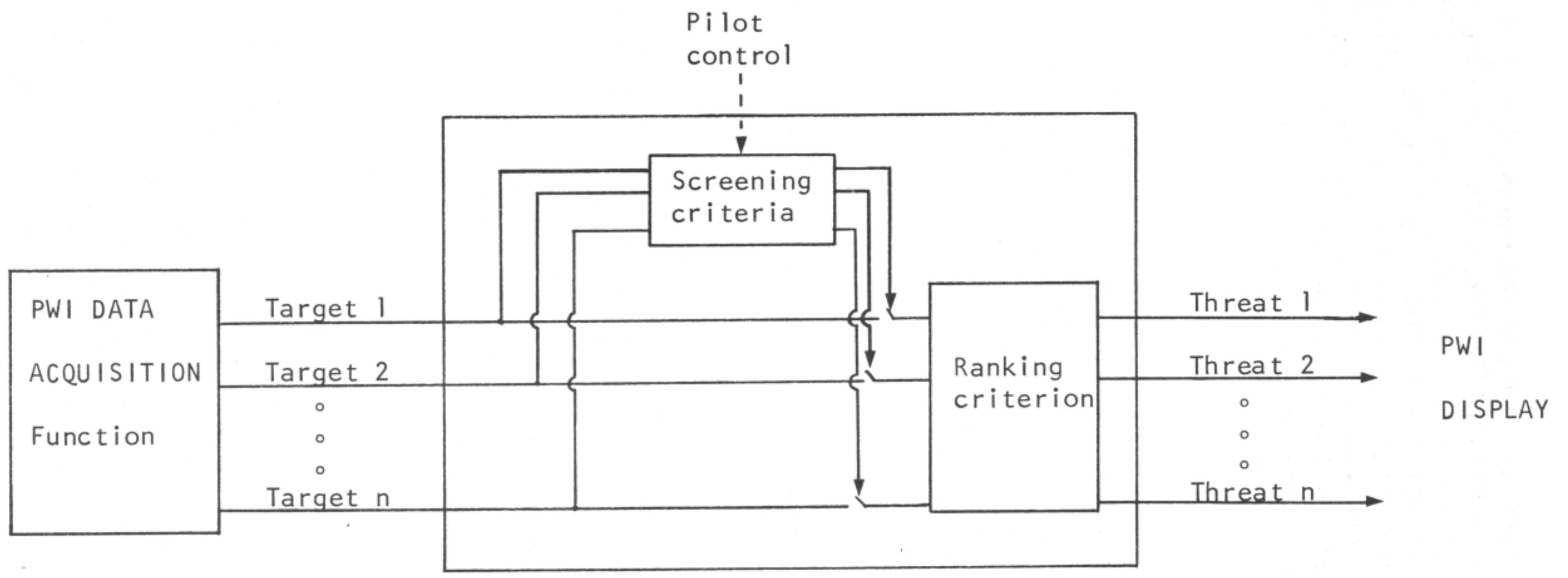


Figure 9. PWI SCREENING Function

for those targets that have survived the screening tests. This target information now goes directly to the PWI DISPLAY function. In addition to screening the targets, this function could also be used to assign priorities to targets in the case of the detection of simultaneous targets. By ranking the targets in their order of threat the PWI would provide the pilot with valuable guidelines during extremely stressful conditions. As an example, a recent CAS simulation study (21) used the lowest value of the product $\tau x \Delta Z$ as a ranking criterion for a multiple threat situation.

5. PWI DISPLAY Function

The activities of the PWI are culminated in the presentation of the PWI information to the pilot. The PWI DISPLAY function transforms the data coming from within the PWI into an explicit physical form; visual, auditory, or tactile, and presents it to the pilot. This function is the only evidence of the activity of all other aspects of the machine portion of the PWI device. It also constitutes one of the two man-machine interfaces, the other one being the PWI control panel. It includes all communications from the machine to the man, as indicated in Figure 10.

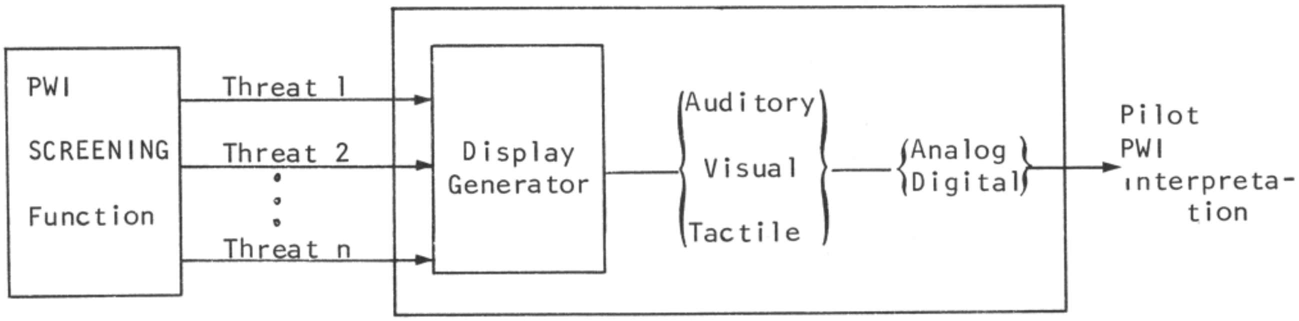


Figure 10. PWI DISPLAY Function

The two major characteristics of the PWI DISPLAY function output are the information content and the information format. The output of the PWI DISPLAY function is solely the transformation of input data into an output format, plus or minus a certain amount of addition or loss which occurs in the transformation process. The content of the information output is dependent on what has occured in previous PWI functions, specifically PWI DATA ACQUISITION. The parameters displayed, their updating, resolution, and accuracy must all be consistent with the preceding functions. Except for self-generated noise, the display adds nothing to the content. As a rule, displays put less information out than they take in.

The output information format is categorized as visual, auditory, tactile, or a combination of these. It is further classified into analog (meter dials, stimulus intensity, etc.), or digital (enunciator panels, digital meters,etc.).

The range of abstraction is wide for both classes, ranging from completely numerical presentations to graphical and pictorial displays.

Two examples of prototype displays developed to date are shown in Figures 11 and 12. From a human engineering standpoint they are both substantially wanting. However, in all fairness to the designers, the concept shown in Figure 12 was never intended for serial production and widespread use in the small general aviation cockpit. Even so, it is difficult to see how any PWI system could get a fair evaluation trial with this display. These two examples of displays, however, do illustrate some of the difficulties involved in presenting a quantity of PWI information to the pilot in a minimum of space.

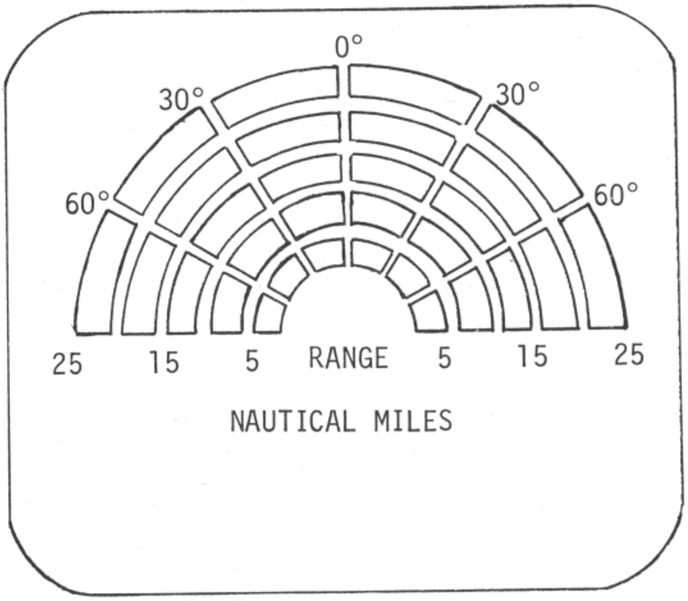


Figure 11. PWI Display (from reference 16)

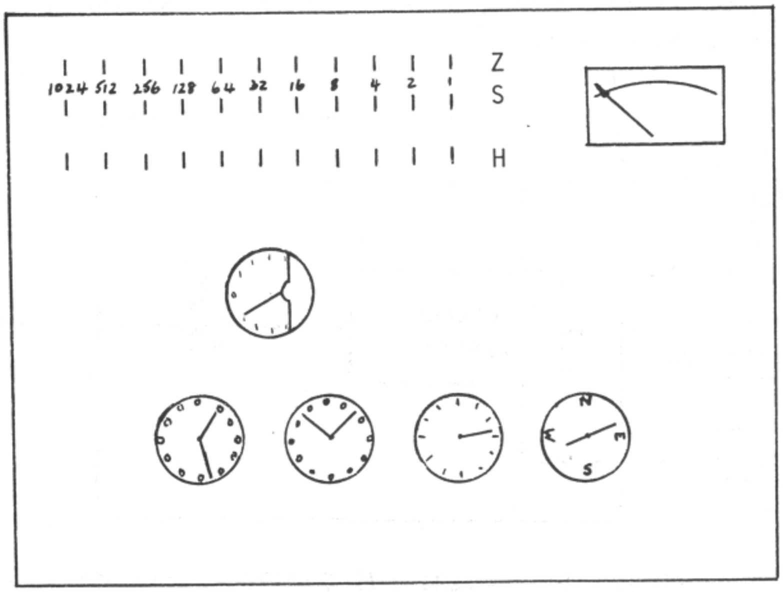


Figure 12. PWI Display (from reference 14)

B. PILOT FUNCTIONS (Man Functions)

1. PILOT-PWI CONTROL Function

The reverse mode of PWI-to-pilot communication is that of PILOT-PWI CONTROL. This function, the first of the pilot functions listed here, permits the pilot to impose direct control over the behavior of the PWI functions as shown in Figure 13.

Since this is a pilot function, it is subject to variations in the way different PWI's are used because of differences between one pilot and another in attitude, experience, intelligence, and alertness, to name a few sources. There will also be variations even within the same pilot from time to time. In some cases there will be definite stimulus-response patterns set up in which the pilot makes a given set of responses to the situation at hand. In other instances, controls may be set purely according to a pilot's preferences or may be left in some setting (perhaps an inappropriate one) due to simple inattention or lack of understanding.

The inputs to this function come from several sources (as seen in Figure 13). For one thing, this is the basic way of setting up the PWI device so it must have on-off functions, perhaps brightness controls, sensitivity controls, squelch controls, etc. Referring to Figure 3, the pilot may see the target before the PWI reports it in the display. He may, therefore, re-address the controls of the PWI because he feels that it is not functioning correctly. It may be speculated that pilots will be tempted to tinker with the controls of the PWI rather often. One reason is that the range of the PWI may be relatively short (perhaps deliberately so in order to reduce false alarms) so the pilot may frequently see aircraft that do not show on the PWI display. This may cause attempts to improve the sensitivity of the PWI in order for it to "see further." A number of other examples of pilot mistrust, or desire for more data, could be cited. Another motivation for the pilot may come directly from the PILOT THREAT EVALUATION function, which encompasses all decision-making processes of the pilot. Once a decision has been made to alter some behavior of the PWI, the PILOT-PWI CONTROL function enables the execution of that decision.

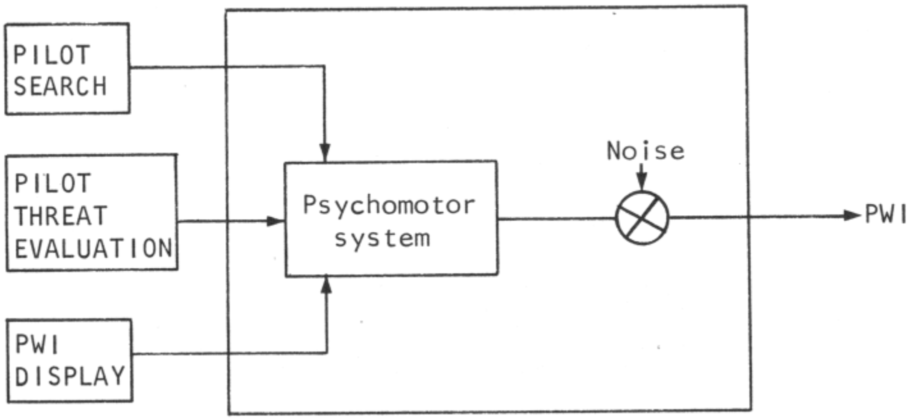


Figure 13. PILOT-PWI CONTROL Function

As the reverse of the PWI DISPLAY function, the process involves one of transforming information from within the pilot into an explicit machine input. Noise again enters into this process and is expressed stochastically in such things as accuracy with which a pilot can set a continuous control, or the speed with which he can key in digital inputs.

2. PILOT SEARCH Function

This function describes the pilot's means of visually searching for other aircraft in the airspace surrounding his own aircraft. Its characteristics are essentially similar in type to those of the PWI SEARCH function; that is, it specifies the instantaneous visual search axis vector, $\vec{E}$, the time history of this vector's movement, and the total field that is searched visually. Affecting these characteristics are visibility conditions imposed by the outside environment, visibility limitations of the cockpit windscreen and windows, and numerous other psychological training, and experience parameters influencing the pilot's scanning pattern.

As will be noted, there are PWI SEARCH and PWI DETECTION functions just as there are PILOT SEARCH and PILOT DETECTION functions. Taken together, these all work to form the basis for the overall search and detection process. The total process has been deliberately divided into these component functions and separately discussed in order to emphasize the difference in their characteristics and to focus on the respective importance of each function. In general, data on the visual detection process in man possesses an undesirably large amount of variability from one subject to the next. In carefully controlled experiments in which the searching process is eliminated by providing the subject with a fixation point, the data are less variable and fall along classical detection curves.(6) This would suggest, then, that much of the variability in performance for the free search experiments stems from the efficiency of the subject's search technique itself.

Detection of targets with respect to the visual axis often presents the appearance of being a more or less involuntary psychophysical phenomenon with gross eye movements being made essentially voluntarily and other aspects of the task being "natural" or "instinctive." We are not inclined to this view, however; being rather disposed instead to the view that detection is a deliberate, purposive activity possessing definite cognitive as well as sensory-motor attributes. If visual detection seems to be an involuntary human activity, it presents this appearance because of the high degree of overlearning associated with a lifetime of detecting things and therefore, the seeming facility with which the action is completed. The best evidence for this view is the improvements which can be made in reading speed and reading comprehension which can result from systematic training. A substantial part of this improvement comes from changes in patterns of detection. Search patterns are learnable as are other eye movements involved in flying (i.e., instrument scanning). More important though, is the fact that such patterns can be theoretically optimized in the sense of maximizing the opportunity for target detection. (23) With this potential for increased detection performance through better search techniques in view, the PILOT SEARCH function was established to isolate this concept and study it more closely.

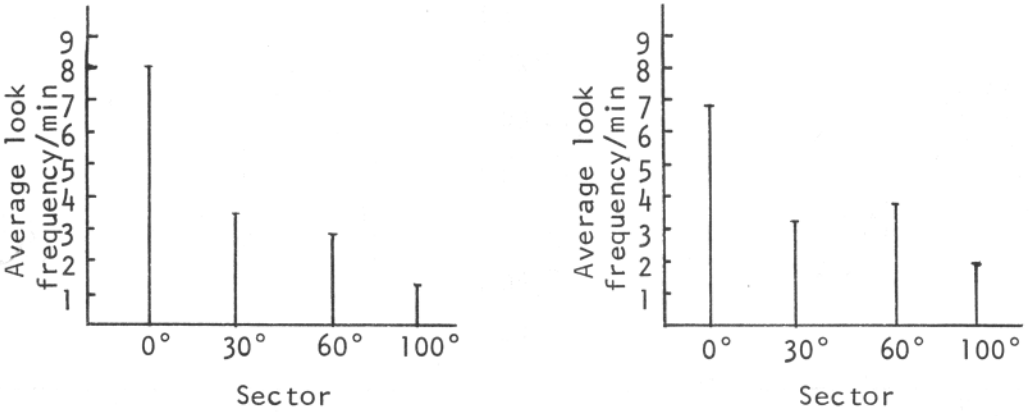
There are three major semi-autonomous processes within this function. The first of these is the scan ratio process which specifies the amount of time the pilot devotes to inside-the-cockpit visual scanning chores and to outside-the-cockpit searching. This "inside-outside ratio" is altered to accommodate the pilot's cockpit workload and the pilot's concern over the other aircraft in his vicinity (and is, without question, a very complex blend of pilot experience, attitude, risk-taking propensities, visual capability, and numerous other variables). Second, given that the pilot is looking outside the cockpit, he will spend part of the time fixating on points in space. The significant characteristics of this fixating process are the duration of the fixation, the frequency of fixation and the focus of the visual apparatus. The third major process describes the movement of the pilot's search vector from one fixation point to the next. This is called saccadic movement. It is characterized by the direction and magnitude distributions of the movements.

Data are available in some form or another on all three of these processes although not all are taken from a population of general aviators, nor do all of them concern themselves with the task of airborne target detection. The data which are cited below are selections from a voluminous literature and will probably serve quite well as a first approximation of pilot behavior; however, they should be used with reservation. Further experimental studies in all three of these processes as they apply to the airborne target detection problem are urgently needed.

The only data on inflight scan ratio frequency and duration of scan known to us comes from a study (25) on aircraft conspicuity in which both informed and uninformed subject pilots were used. The tests were conducted while the subjects flew a DC-3 transport aircraft on a preset test course. Histograms of the frequency of look and duration of scan, both as functions of azimuth sectors, were compiled from film recordings of the subject's face and are redrawn in Figure 14.

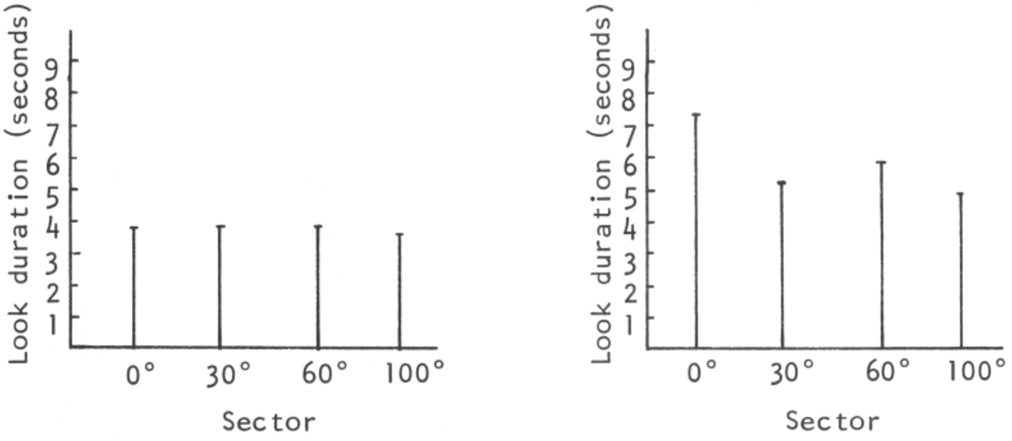
The informed pilots, who were told that another aircraft would be on a collision course with them at some unspecified time during the flight but not told from what direction this other aircraft would come, showed an increase in look duration and a higher look frequency in the 60° and 100° sectors than did the uninformed pilots. The informed pilots also increased the range of target detection by 1.6 miles for the 0° collision course and by 1.3 miles for the 100° situation. Some of the conclusions that can be drawn from this data are that pilots could increase their ability to detect other aircraft by developing better search habits and that provision of some information apparently alters the outcome in a favorable way.

Data on eye movements during the outside-the-cockpit scan were not found for the task of searching for airborne targets. Extensive laboratory data on eye movements during free search (20) were found, however, and are shown in Figure 15. These charts were compiled from electro-oculographic recordings of six subjects whose task was to find a 1/8-inch diameter threshold level target in a 30° circular search field within a 5-second time limit. The average fixation frequency ranged from 2.2 to 4.4 fixations per second with a mean frequency of 3.1 fixations per second. Average fixation duration was 0.28 seconds.



(a) frequency of looks (uninformed)

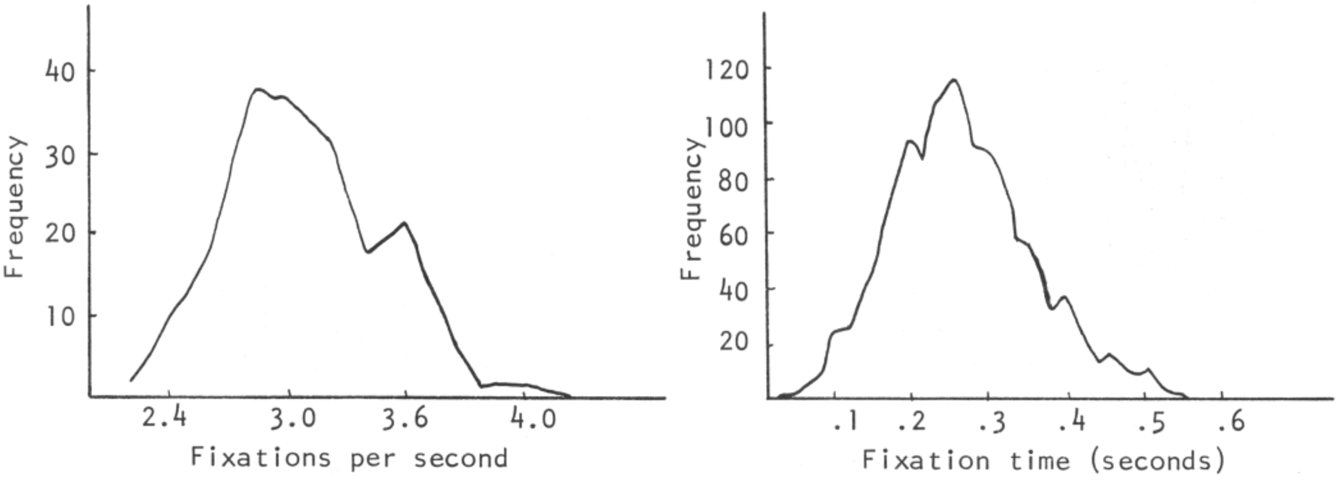
(b) frequency of looks (informed)



(c) duration of looks (uninformed)

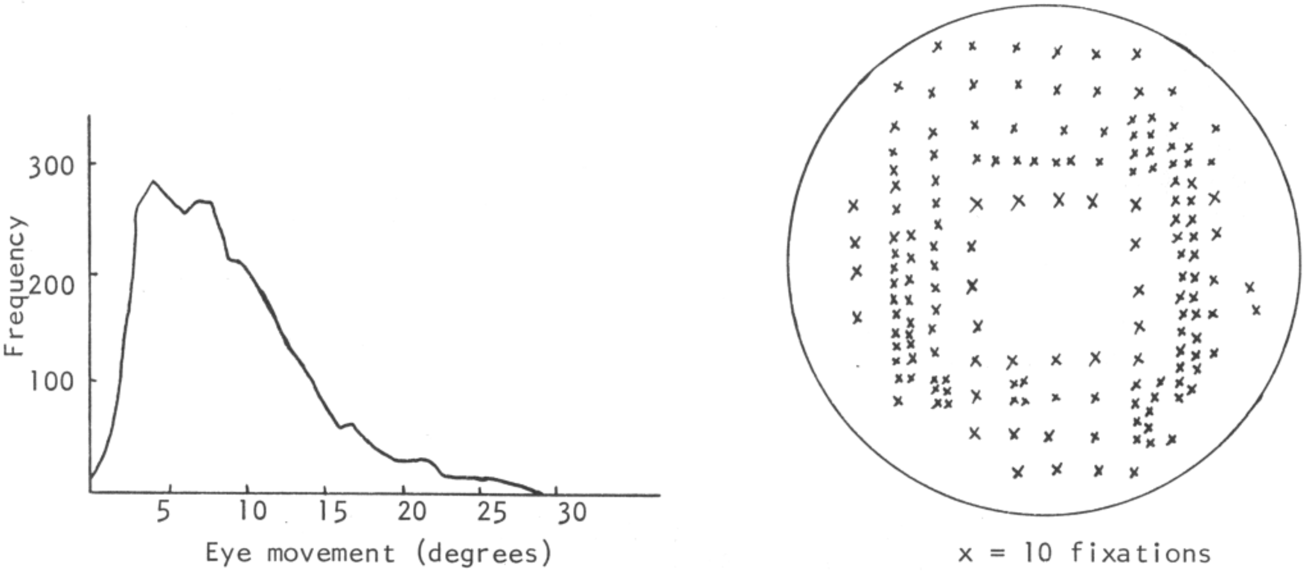
(d) duration of looks (informed)

Figure 14. Experimental Scan Ratio Data
(from reference 25)



(a) fixation frequency

(b) fixation duration



(c) length of saccadic movement

(d) spatial distribution of fixations

Figure 15. Experimental Eye Movement Data
(from reference 20)

Data on the saccadic movements from the same study may be less applicable to the present analysis since the total search field subtended was only 30°. The distributions shown in Figure 15 indicate that within this 30° field the average movement per saccade was 8.60° and the spatial distribution of fixations peaks between the center and the edge of the search field. The average duration of the saccadic movement can be estimated by determining the fraction of time spent in saccades and dividing this by the fixation frequency. The average saccadic duration computed from the data presented is .04 seconds.

To illustrate how these data or more refined versions of them could be used in this analysis, the following mathematical model is proposed. As stated above, the output of the PILOT SEARCH function is the visual scan axis vector, $\vec{E}$, defined as:

$$(11) \qquad \vec{E} = \alpha_e(t)\vec{i}_\alpha + \varepsilon_e(t)\vec{i}_\varepsilon$$

where $\alpha_e(t)$ and $\varepsilon_e(t)$ are the azimuth and elevation angles of the visual scan axis and $\vec{i}_\alpha$ and $\vec{i}_\varepsilon$ are the unit vectors defined in Figure 4c. $\alpha_e(t)$ and $\varepsilon_e(t)$ are generated by the three semi-autonomous processes detailed above.

It has been suggested (47) that in free search the subject's distribution of fixation points is influenced by the shape of the search field boundaries. This is evidenced again by the spatial distribution shown in Figure 15d. In the present instance, the pilot's search field is bounded by the cockpit and window structure surrounding him. As a first step, then, in developing a visual search model, assume the pilot's visual field is partitioned off in zones that follow the cockpit structure, as shown in Figure 16. Zone 1 is the forward windshield; Zone 2 the left window; Zone 3 the right window; Zone 4, the rear window; and Zone 5 inside the cockpit. The time the pilot

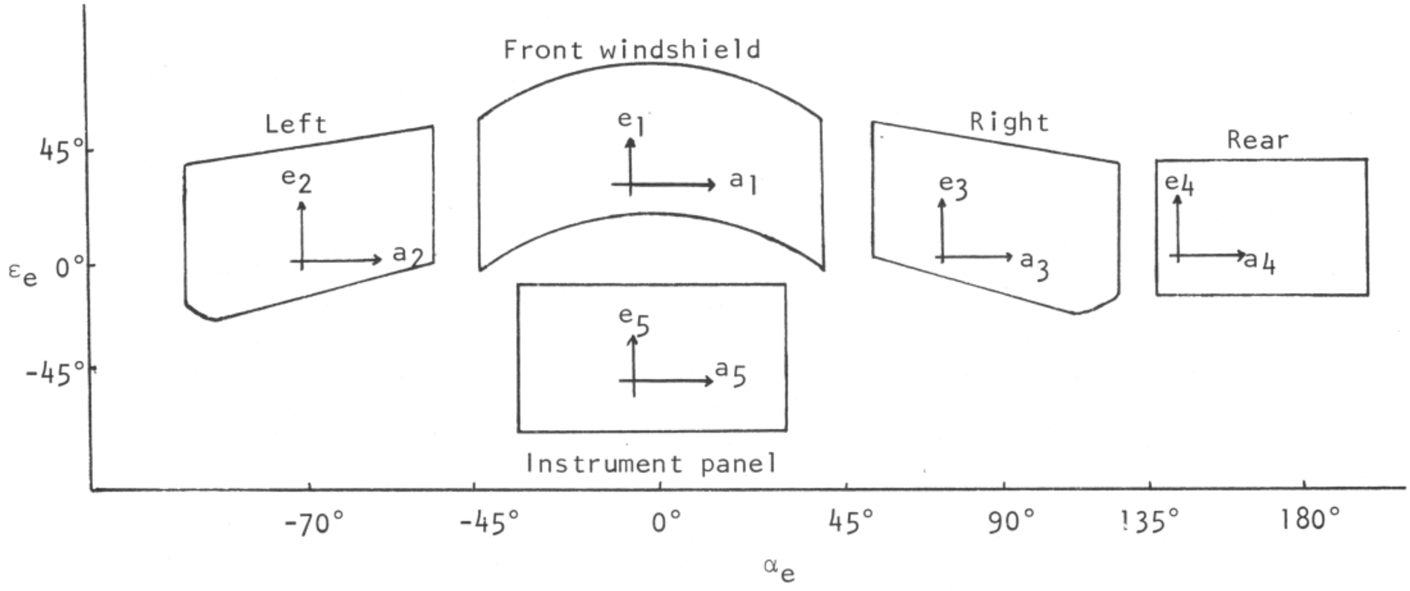


Figure 16. Pilot's Search Field Zones

spends looking in one of these mutually exclusive zones will be defined as "one glimpse." Assume, then, that associated with each zone is a probability, $P_z(n)$, $N = 1, \ldots, 5$, which defines the probability that a pilot will glimpse into that zone. Assume for now that successive glimpses are independent events although after more experimental data is collected they will most likely show signs of some degree of correlation. The duration of the glimpse is also assumed to be a stochastic event; $P_d(t)$ defines the probability that a glimpse will last t seconds. Again, independence between look duration and zone is assumed, although the data in Figure 14 shows an increased correlation between these variables when the subject is informed of the threat. From these two probability functions, $P_z(n)$ and $P_d(t)$, a random discrete time function, $G(t)$, can be generated which simulates the pilot's random glimpsing from zone to zone. An example of a typical time history for $G(t)$ is shown in Figure 17.

While looking in a particular zone the pilot's visual scan axis jumps from point to point, as described by the data in Figure 15. A mathematical model of this motion can be developed in the same manner as was the glimpse model. If within each zone an orthogonal coordinate system is defined, α_n, ε_n, whose original is at the center of the zone and whose axes are parallel to the azimuth and elevation unit vectors described in Figure 4c, then the azimuth and elevation angles of the visual scan vector, $\vec{E}$, can be expressed:

$$\alpha_e(t) = \alpha_{en}(t) + a_n(t) \qquad n = 1, \ldots, 5 \tag{12}$$

$$\varepsilon_e(t) = \varepsilon_{en}(t) + e_n(t) \qquad n = 1, \ldots, 5 \tag{13}$$

where $\alpha_{en}(t)$ and $\varepsilon_{en}(t)$ are the coordinates of the centers of each of the zones with respect to the body axis system of Figure 4c. To generate a stochastic $\vec{E}$ as a function of time, $\alpha_{en}(t)$ and $\varepsilon_{en}(t)$ are determined by $G(t)$ and $a_n(t)$ and $e_n(t)$ are generated by the continuous probability functions $P^n{}_{df}(t)$ and $P^n{}_{a,\,e}(a,e)$ which describe the duration and position of the fixation points within Zone n respectively. $P^n{}_{df}(t)$ and $P^n{}_{a,e}(a,e)$ are derived from the data in Figure 15. A typical time history for the components of $\vec{E}$ is shown in Figure 18. Note that $\vec{E}$ is not defined when the pilot is looking inside the cockpit (Zone 5).

A summary of this function, PILOT SEARCH, is illustrated in Figure 19. The inputs shown function as override controls on the semi-autonomous visual search processes and point out the responsiveness of this pilot function to the instantaneous demands of the environment, the long-term and short-term characteristics of the observer, and the rest of the system. The environmental input air traffic density, for an example, should alter the glimpse distribution functions, $P_z(n)$ and $P_d(t)$, assuming the pilot knows of this traffic and has something other than fatalistic concern for detecting other traffic. This was exemplified in Figure 14.

The input from the PILOT DETECTION function is used here to lock the pilot's scan on the detected target until a "no threat" decision is reached by the PILOT THREAT EVALUATION function.

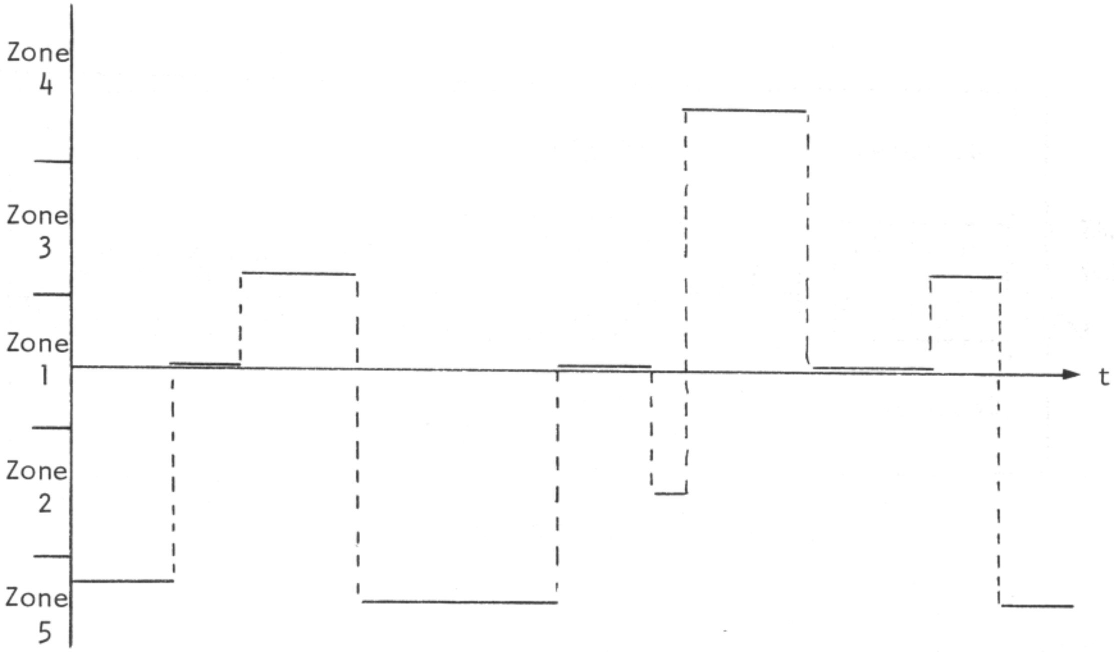


Figure 17. Typical Glimpse Function, $G_1(t)$

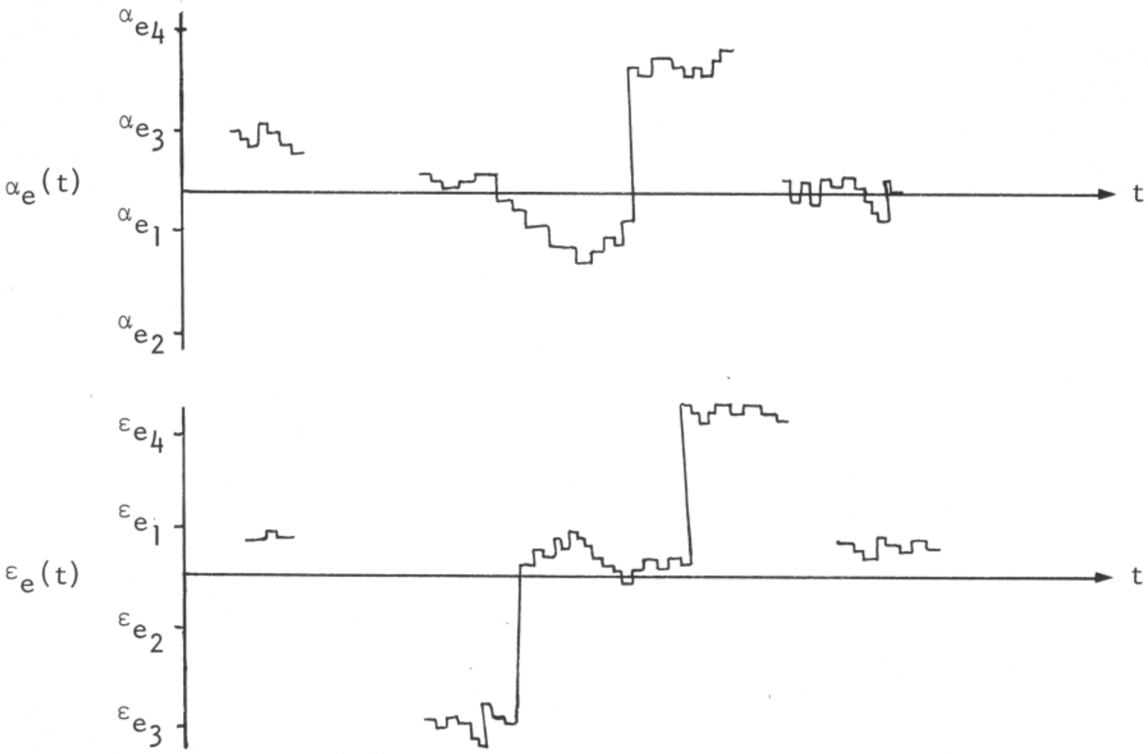


Figure 18. Typical Scan Coordinates, $\alpha_e(t)$ and $\varepsilon_e(t)$

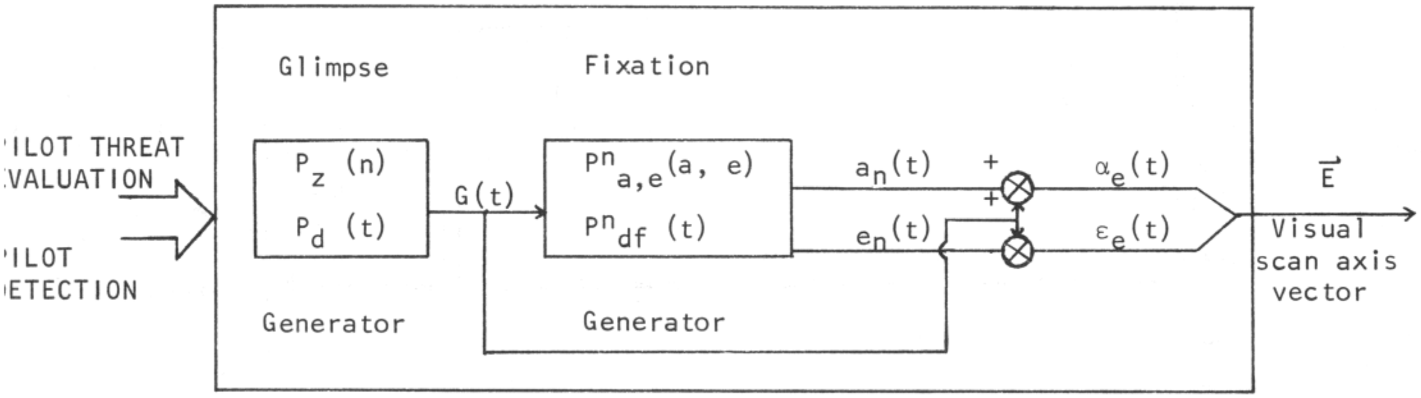


Figure 19. PILOT SEARCH Function

3. PILOT ALERTED SEARCH Function

The pilot function is structurally identical to the above PILOT SEARCH function, as shown in Figure 20. It has the same three semi-autonomous processes. However, it is a distinct functional mode because it represents the pilot's response to a PWI alarm and the values of the stochastic parameters which describe the search function are very likely directly related to the characteristics of the PWI being used. The exact relationships between the PWI characteristics, the data it presents, and its reliability, and their effect on the pilot's search parameters has not yet been determined. Nonetheless, some positive experimental evidence exists (9) that demonstrates the increase in detection performance achieved through providing the pilot with target information.

This function is employed to narrow down the search field, increase the intensity of the search, and give priority to outside-the-cockpit scanning. In this analysis, the input to this function is the pilot's interpretation and evaluation of the data supplied by the PWI. This original PWI input may range from a simple warning buzzer to a precise indication of target position. In any case, it is processed through the PILOT THREAT EVALUATION function then sent to the PILOT ALERTED SEARCH function to set the values for the scan distribution probability functions.

The duration of this function is determined by either the detection of a target or by the pilot's decision that the PWI had given a false threat alarm. In the latter case, a system with a high false alarm rate (i.e., an alarm but no visibly detectable target) may only call for a short alerted search scan followed by perhaps two or three such scans moments later. Experiments on a pilot's behavior under these conditions have been conceived by the authors and are currently being conducted at the FAA's National Aviation Facilities Experimental Center, Atlantic City, New Jersey.(19)

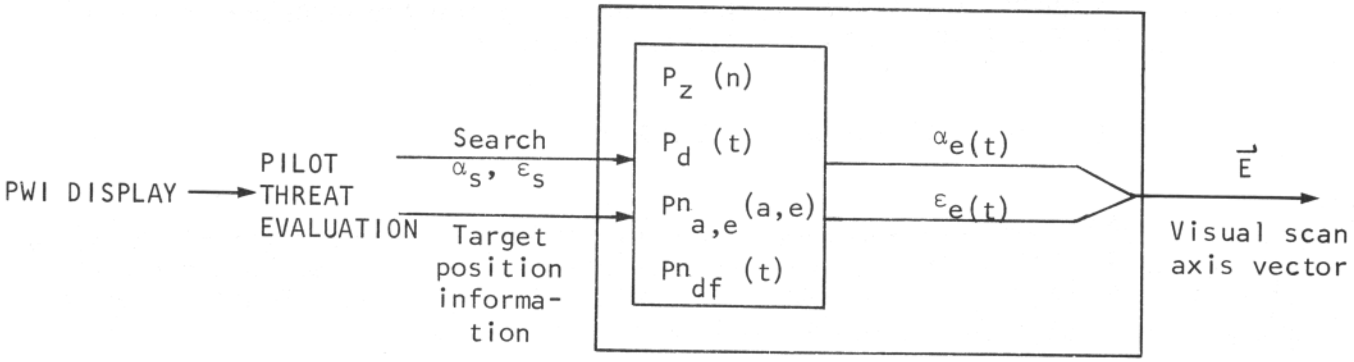


Figure 20. PILOT ALERTED SEARCH Function

4. PILOT DETECTION Function

This function, as in the case of the PWI DETECTION function, relates the presence of a target in the visual field to the conscious perception of the target. The inputs to this function are the target position vector, $\vec{T}$; the visual scan axis vector, $\vec{E}$; the status of such things about the target as its angular size ω_t, and brightness; and the visibility and background luminance of the environment.

The output of this function is described by a multi-dimensional detection probability function, P_{pdet}, which is a function of the inputs listed above. Considering the fact that foveal vision, the area of maximum detection in the visual field, subtends only a small portion of the visual field, the position of the target in the visual field becomes the most critical factor in the detection probability.

In contrast to the modelling efforts of the previous function, PILOT SEARCH, much more has been accomplished in establishing mathematical models of target detection with respect to the axis of the scan vector. One of the more simplified models (43) suitable for the purposes of the present analysis computes the angle, δ, off the foveal axis at which a target is detectable 50% of the time. This computation is based on empirical data involving the apparent contrast ratio of the target and the angular size of the target.

The apparent contrast ratio of the target is derived from the inherent contrast ratio which is defined as follows: if B_o is the luminance of the background and B_{ot} is the luminance of the target, then the inherent contrast ratio of the target, CR_o, is:

$$CR_o = \frac{B_{ot} - B_o}{B_o} \qquad (14)$$

The apparent contrast ratio is the inherent contrast ratio attenuated by the atmospheric conditions between the target and the observer. In a simplified format, this relation can be expressed as: (15)

(15) $$CR = CR_o \; e \; -3.912 \; R_t/v$$

where CR is the apparent contrast ratio, R_t is the range to the target, v is the meteorological visibility in the same units as R_t. More elaborate descriptions of the apparent contrast ratio include line of sight angles, zenith angle of the sun, path radiance, and beam transmittance. (8)

The empirical relationship (43) between the apparent contrast, CR, the target diameter, ω_t, and the threshold detection angle off the foveal axis, δ, for 50% detection is

(16) $$CR = 1.75 \; \delta^{1/2} + 19\delta/\omega_t{}^2$$

The target diameter, ω_t, in minutes of arc is given by:

(17) $$\omega_t = 1293 \; A^{1/2}/R_t$$

where A is the aspect view area of the target in square feet. Assuming A is relatively constant for a given collision condition and substituting equations (14), (15), and (17) into equation (16), using the nominal bright daylight value of 1000 foot-lamberts for B_o, the threshold relationship can be reduced to a function of two variables, R_t and δ:

(18) $$[(B_{ot} - 1000)/1000] \quad e^{-3.912 \; R_t/v}$$
$$= 1.75 \; \delta^{1/2} + 19\delta/A[1293/R_t]^2$$

where A, B_{ot}, and v are constants for a given set of conditions. The meaning of equation (18) is that the probability of target detection function, P_{pdet}, can be reduced to a function of two dynamic variables, target range and the angular position of the target off the foveal axis, and a set of static variables, target size, luminance, and visibility.

Equation (18) gives only the locus of points for $P_{pdet} = .50$. To complete the formulation of the rest of the function, P_{pdet}, probability conversion factors have been determined (7) which convert the threshold contrast ratios found at the 50% detection level to those ratios found at the 90%, 95%, and 99% levels. These factors, which multiply the left side of equation (18), are 1.50, 1.64, and 1.91 respectively. Inserting these factors in equation (18) and solving it for each one generates the locii which make up the P_{pdet} = .90, .95, and .99 portions of the total function. The remainder of the probability function can be found by curve fitting techniques as sketched in Figure 21.

A structural model of the PILOT DETECTION function is shown in Figure 22. The data required for the probability of detection computations are shown on the inputs. The output is the number of targets that have been detected at any given instant of time, $n_{pdet} = 0.1, \ldots$. This information acts as a trigger to other pilot functions; it activates the PILOT TARGET INTERPRETATION function and commands the PILOT SEARCH function to zero in on a target and track it until a threat evaluation can be made.

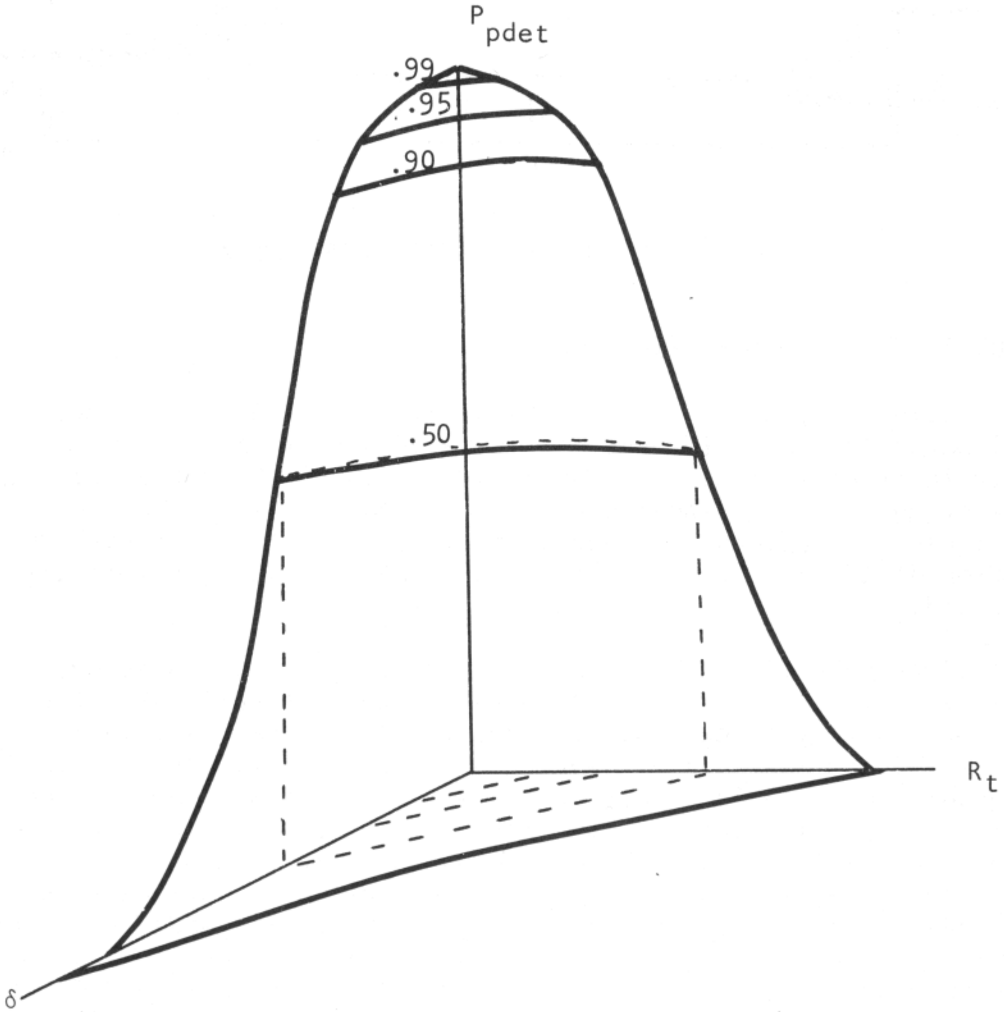


Figure 21. Pilot's Probability of Target Detection

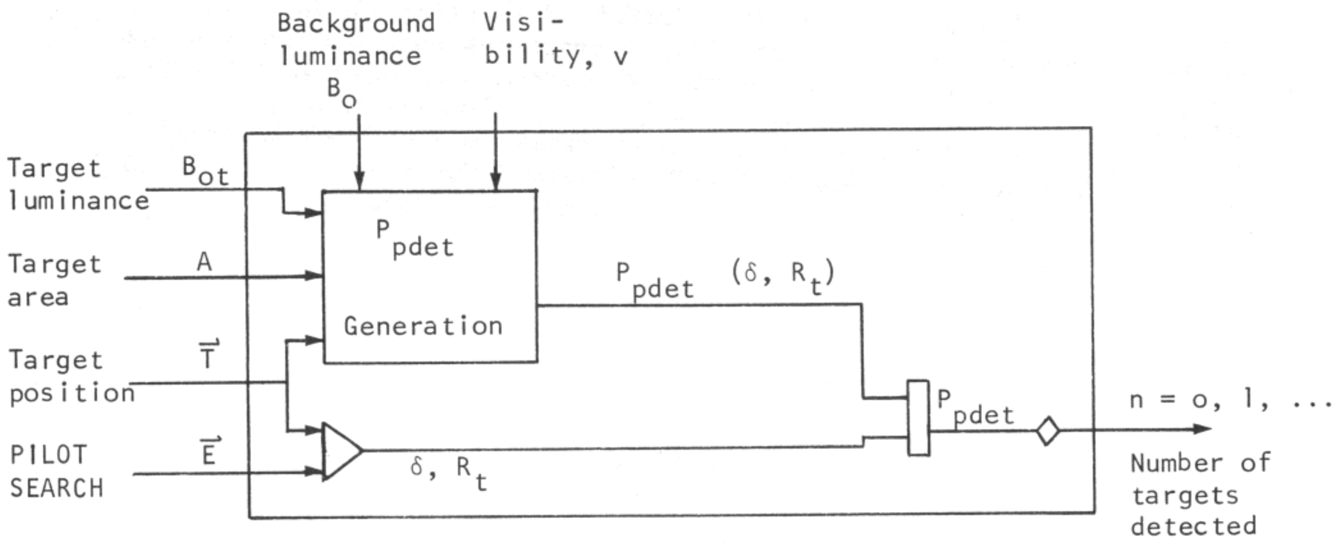


Figure 22. PILOT DETECTION Function

5. PILOT TARGET INTERPRETATION Function

Once having detected a target, the pilot must visually estimate the geometrical parameters of the target not provided to him by the PWI and yet necessary in order to make a rational evaluation of the target as a threat. The lack of quantitative knowledge of the mechanisms and cues used by pilots to make these estimations and the difficulty in obtaining direct experimental data confounds the problem and allows only the crudest models of this function to be generated.

The estimations of parameters such as range, position, heading, relative velocity, and relative altitude are often quite difficult tasks for the pilot and are occasionally susceptible to gross inaccuracies, especially at night or in foul weather when visual contact with ground references is inadequate or altogether absent. The opportunity exists to further explore these gross misjudgments, or illusions as they are often called, within the structure of this function, PILOT TARGET INTERPRETATION, however, at this point in the analysis, they are excluded from further consideration for they would tend to confuse the more basic issues surrounding the PWI. They have been noted here to indicate how they might be handled analytically in the future. Also, the reader should be informed that, as another part of the present contract, Rowland & Company is developing both analytic and experimental studies in these areas.(39)

The investigation of the PILOT TARGET INTERPRETATION function need not imply that a pilot explicitly estimates target parameters in numerical terms. In fact, a conscious numerical estimation of range or range rate may be the exception rather than the rule. In threatening situations the pilot really has no need to convert his impressions of the target information into numerical terms except to convey this information to an outside party. One might expect an experienced pilot to perceive the target parameters and make an evaluation with such rapidity that he would not be conscious of any numerical computations in reaching his decision, in fact, he may never even resort to numerical concepts at all but may use other logical perceptual processes of non-mathematical nature entirely. Be that as it may, the pilot does make his judgment using some criterion and his decision is based, at least in part, on his perception of the situation and his interpretation of the target parameters.

As illustrated in Figure 23, the input to the PILOT TARGET INTERPRETATION function comes from the environment, the detected target. The visual image of the target is compared with past experiences of the pilot and from this an estimation of the target parameter is made. The dependence of this estimation on past experience is corroborated by a study (4) which showed marked improvement in a subject's ability to estimate air-to-air range after receiving training which consisted solely of immediate knowledge of results.

In many instances, the pilot cannot confidently make an estimation of a target parameter either because of the acuity limitations of his own eyesight or because the field against which the target is presented contains no structure or reference points to aid the pilot in his perception. Accordingly, in this present analysis, provisions have been made to accompany each estimation (R_{pt} in the example shown in Figure 23) with one of two levels of confidence, g for guess and c for certain. Thus, R_{ptg} would be a pilot's interpretation of target range wherein he was not certain of his estimated value. These levels of confidence are not meant to be absolute levels of certainty from a mathematical or statistical standpoint but are a reflection of the pilot's confidence in his estimate. The purpose of including these confidence levels in the output of this function will become evident in the description of PILOT THREAT EVALUATION function.

This particular aspect of the pilot's behavior is worthy of much more extensive investigation experimentally. Experiments that have been conducted (4) on the ability of pilots to estimate one of the most important target variables, range, show variations in the range error with the size of the target aircraft, day and night viewing conditions and, most noticeably,

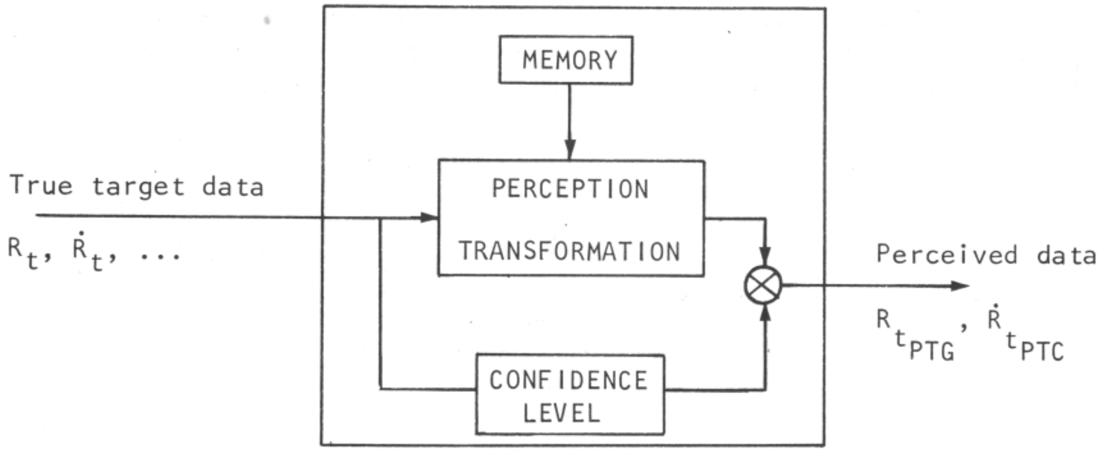


Figure 23. PILOT TARGET INTERPRETATION Function

with flying experience. The net result was a constant overestimation of range on the order of 1 to 2-1/2 miles by the experienced pilots (greater than 900 hours flying time) and on the order of 5 miles by the inexperienced pilots. At night, the range error fell from a 3-mile error at an actual range of 2 miles to no error at an actual range of 7 miles.

Data on relative altitude estimation errors (4) indicate that pilots are capable of judging relative altitude within ±500 feet 90% of the time at distances up to two miles during daylight hours. Judgments within ±500 feet at night are made correctly 43% of the time at 2 miles range and fall off to correct judgments 18% of the time at a 5-mile range.

Estimates of bearing angle rates,(9) a parameter quite significant in threat evaluations, indicate a miss decision (i.e., a perception of bearing angle movement) threshold level at a rate of 10 minutes of arc/sec for a cloud-structured field and at a rate of 18 minutes of arc/sec for an unstructured field.

6. PILOT-PWI INTERPRETATION Function

The reader will recall that, by definition, a PWI system aids the pilot in target detection and evaluation but must leave all decision making to the pilot. As a result, to accomplish its prime objective of aiding the pilot, the PWI must be able to effectively communicate its information to the pilot.

The presentation of data by the PWI has already been discussed under the PWI DISPLAY function. The second half of PWI-pilot communication, the reception of the PWI information, is covered by the PILOT-PWI INTERPRETATION function. In this present function the data displayed by the PWI is converted into the information consciously perceived by the pilot.

The basic intent in delineating a PILOT INTERPRETATION function is to provide a grounds for studying the processes associated with transformation of the information presented to the pilot into the information used by the pilot as manifested in his actions. Thus, within this function the output of the PWI display is quantized, weighted, extrapolated, and interpolated, as indicated in Figure 24, and its output, the transformed information, goes directly to the PILOT THREAT EVALUATION function where it is utilized to direct the cognitive processes which act upon these inputs.

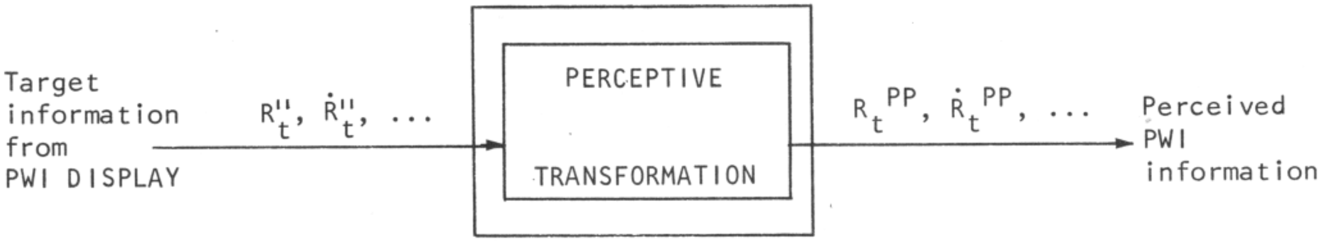


Figure 24. PILOT-PWI INTERPRETATION Function

The relation of this function to the entire analysis is quite straightforward. It would be useless to develop a PWI system that would present data to the pilot that is far more precise and accurate than the interpretation he is going to give to it. Indeed, there is substantial human engineering data to suggest that too much information in too detailed a format may actually contribute to a significant deterioration in display interpretation. It would be irresponsible to present a pilot with PWI information that is ambiguous or easily misinterpreted. It is quite possible, then, to have the utility of a PWI system completely vanish by overlooking this pilot function. In spite of the tremendous importance of this function, little effort to date has been devoted to studying the pilot's speed in interpreting PWI, the reliability and accuracy of his interpretation, and the relation of all of these to the information content and format. Relevant research in this critical system design area is needed badly.

Until further experimental evidence is found, the process involved in this function can perhaps best be modelled by a simple unity gain time delay.

7. PILOT THREAT EVALUATION Function

The ultimate function of the pilot, regardless of the PWI hardware subsystem being used, is contained in the PILOT THREAT EVALUATION function. It is in this function that the outputs of the PILOT TARGET INTERPRETATION function and PILOT-PWI INTERPRETATION function are integrated and inserted into a decision-making criterion from which all pilot actions are derived.

The essence of this function is contained in the decision-making criterion and logic behind the pilot's judgments. By far the most important decision to be made is the collision threat decision. Based on the data perceived by the pilot, a decision must be made on the likelihood of a collision with the detected target. The criterion used for the decision may range from an easily stated rule such as the constant bearing angle criterion to a much more complicated trajectory prediction technique. As already stated, the experienced pilot may not even be cognizant of the actual decision he is using, though in the broadest sense he is using one, however imprecise, for the fact that he makes an avoidance maneuver indicates that he has made some type of decision.

The commonly used decision criteria have developed either from a mathematical analysis of the collision situation or have evolved as a learned reaction mechanism of the pilot as he acquires more and more flying skill. Seven criteria are listed here as representative of both mathematically derived and human behavioral decision-making methods.

(1) Target position and closing velocity - This criterion is the embodiment of the present right of way rules for overtaking another aircraft. The rules apply in general and are not just for collision situations. However, by consistently following these rules, the pilot may build up more or less of a reflex-like reaction which would predominate his behavior should an actual collision situation arise. The rules (18) generally state that if a closing velocity exists between two aircraft, then, in the head-on approach both give way to the right; in tail approaches the overtaking aircraft gives way to the right; and in the abeam approach, the aircraft

to the right has the right of way. Unofficial rules (26) based on the relative position of the other aircraft include climbing and diving maneuvers as well.

(2) Range - This, the simplest of all criteria, uses only the range between the aircraft involved as the decision criterion. All aircraft entering a protected volume surrounding the pilot's aircraft are considered as threats and an appropriate action is taken by the pilot to maintain separation above some level established by rule or judged appropriate by the aviator himself.

(3) Trajectory Prediction - This technique requires a subjective estimation of the threatening target's trajectory with respect to the extended trajectory of one's own aircraft. This, in itself, relies heavily on a pilot's experience and skill plus a substantial amount of perception applied to sensory cues. It is possibly the approach used most often in the case of those pilots who claim an intuitive sense of collision danger.

(4) Constant relative bearing angle - This method is based on the geometrical fact that the relative bearing angle between the protected aircraft's flight path and the line-of-sight to the target is stationary only for collision trajectories.

(5) Constant relative bearing angle and closing range - In order for a collision to occur under the previous criterion, obviously a closing range rate is needed. At high closing velocities when a decision must be made while the target is still at a considerable range, neither of these two parameters are that sufficiently evident to the pilot. If, however, with the aid of the PWI he is able to obtain one or both of these, he can begin to make his decision.

(6) Tau - This technique is an outgrowth of a mathematical analysis (29) of the collision situation. Tau is the ratio of target range to target range rate and it predicts the time until collision or closest approach. Depending on the responsiveness of the protected aircraft, a minimum Tau is set, below which a target is considered a threat. Although in actual use, this criterion would require reasonably accurate range and range rate measurements the pilot may be able to use an intuitive version of Tau by integrating the concepts of range and range rate in his decision.

(7) Tau with a range guard - One weakness in the Tau criterion is its vulnerability to the slowly approaching target as in the case of one aircraft slowly descending upon another. The addition of a minimum permissible range guard to the Tau criterion shields the protected aircraft against this possibility.

Using any one of these decision criteria in conjunction with the target data and its associated confidence level, as obtained from the PILOT TARGET INTERPRETATION and PILOT-PWI INTERPRETATION functions, the following hypothetical decision model is proposed as representative of the pilot's true course of action in collision situations. Taking into account the data itself and the levels of confidence expressed in the data, five decisions can be reached by the pilot:

1. the target is definitely not a threat;
2. the target probably is not a threat;
3. no decision on the target can be reached at this point;
4. the target probably is a threat; and
5. the target definitely is a threat.

The subsequent actions taken by the pilot reflect the confidence levels of the decisions as illustrated in Figure 25. Decision 1, the target is definitely not a threat, returns the pilot to his initial searching pattern and if conditions remain unchanged no further consideration is given to the target. Decision 2, the target probably is not a threat, also returns the pilot to his initial searching pattern, however, in this case the target is re-evaluated periodically until some other decision is reached for the target. If Decision 3 arises, which is really the decision that no threat decision can be reached at this time, the target remains under surveillance (full time or part time) until further target information can be obtained. Decision 4, the target probably is a threat, calls for a mild evasive action on the part of the pilot with continued surveillance of the target. Decision 5, the target is definitely a threat, calls for a full evasive maneuver and the complete attention of the pilot on the target. In a case of Decision 5, the target is constantly re-evaluated until it can be down-graded as a threat.

In addition to the principal threat evaluation decision itself, there are two ancillary decision making processes which have been assigned to the PILOT THREAT EVALUATION function and which take place prior to the detection of a target. The first of these governs the pilot's control of the PWI. Once

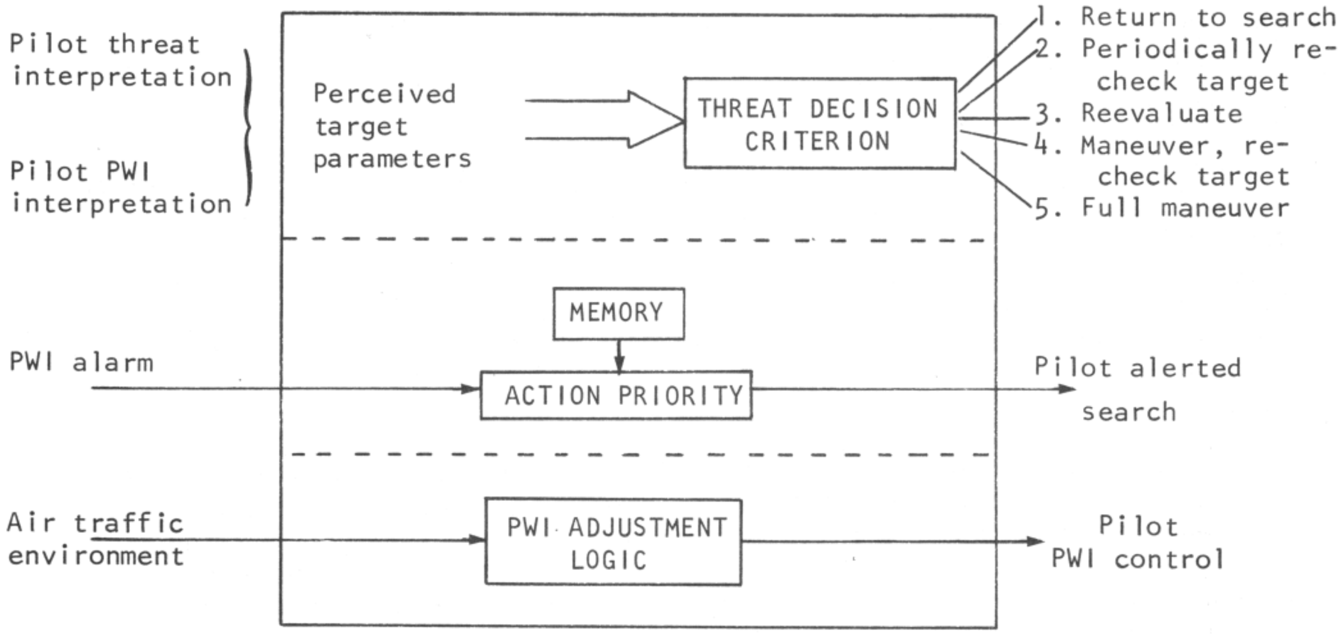


Figure 25. PILOT THREAT EVALUATION Function

the air traffic situation has been evaluated as light or heavy, or local vs. en route, or some other criterion, the pilot may want to adjust the sensitivity of the PWI in order to optimize the selectivity of the system for his particular purposes. The capability to permit controlled reduction in unwarranted alarms for crowded traffic areas may be a necessary characteristic in all PWI systems. In the previous PWI functions, provisions have been made for pilot inputs through the PILOT-PWI CONTROL function. It is the PWI control decision process in the present function that supplies the inputs to the PILOT-PWI CONTROL function. Exploiting the adaptability of pilots through this decision-making process may significantly increase the flexibility and effectiveness of even the simplest of PWI systems.

The second ancillary decision-making process occurs at the instant the pilot receives a PWI alarm. This process assigns the temporal order and priorities to the pilot's task in the time interval succeeding the PWI alarm. The output of this process is essentially a mode control on the pilot's search functions, switching him from normal search to alerted search and back again when the danger has passed or it has been decided that a false alarm was given. To a great extent, the characteristics of the PWI system will determine the characteristics of this process. For example, the pilot's willingness to interrupt his other cockpit duties, which may also be critical at this time too, and the amount of time he will spend in the alerted search mode will most assuredly be related to his personal interpretation of the credibility of the PWI alarm.

Rowland & Company designed, and the Aircraft Branch of the Test and Evaluation Division of NAFEC has run, an experiment on the effect of various PWI systems which were 1) no PWI operating; 2) twice as many alarms as targets (oversensitive PWI); and 3) half as many alarms as targets (undersensitive PWI). The results showed that having either kind of PWI led to a greater number of detections than having none. Time to find targets was less with either type of PWI than with no PWI.(19)

8. PILOT MANEUVER Function

This function transforms the output decision of the PILOT THREAT EVALUATION function into pilot control actions and the resulting aircraft motions. The output of this function is the change in the position of the pilot's aircraft with respect to the originally intended course and, hopefully, a reduced probability of collision. In order to accomplish this, the function must take into account: 1) the reaction time of the pilot, 2) the set of control movements available to the pilot, and 3) the dynamic response of the pilot's aircraft, as shown in Figure 26.

The principal aircraft controls available to the pilot of a fixed wing aircraft are the stick movements which control elevators, δ_e, ailerons, δ_a; the rudder pedal movements which control rudder, δ_r; and the throttle setting, δ_t. The aircraft responses to these inputs are customarily expressed in terms of transfer functions which relate output parameters such as the aircraft pitch angle, θ; bank angle, ϕ; airspeed, V_a; altitude, h; etc., to the control inputs, δ_e, δ_a, δ_r, and δ_t. Such detail is not really necessary for this analysis since the principal maneuvers of concern here can be categorized simply as climbs, dives, and turns. Each of these is a

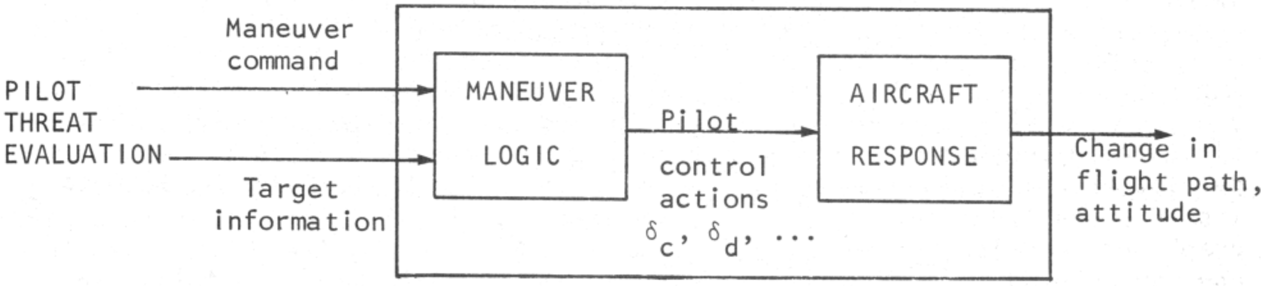


Figure 26. PILOT MANEUVER Function

coordinated combination of the above pilot controls and aircraft responses. Assuming, for this analysis, the pilot makes coordinated maneuvers, the control inputs to the aircraft can be specified as the composite inputs for climbs, δ_c; dives, δ_d; right turns, δ_{rt}; and left turns, δ_{lt}. The aircraft responses are change in altitude, h, and change in heading, ψ. Associated with each response are the corresponding pitch angle for maximum rate of climb, θ_{mrc}, and bank angle, ϕ_c for coordinated turn.

In the model proposed for this function, the decision to make a maneuver along with the pertinent target information for the maneuver logic is received from the PILOT THREAT EVALUATION function. This information passes into the maneuver logic which determines the proper pilot control action as shown in Figure 26. One of the important reasons for establishing this function is to allow the maneuver logic itself to serve as one of the major characteristics of the overall pilot-PWI system. The analysis of collision avoidance techniques can hardly stop at the point of detecting and evaluating threats and leave the maneuver to the pilot's imagination. The collision has not been avoided until a safe pass between all the aircraft involved has been made. This type of analysis cannot be performed without considering the reaction time of the pilot and the time response of the aircraft.

Presently, the only universal guidance the pilot has on maneuver strategy must be extracted from the Federal Aviation Regulations (18) on aircraft right-of-way. This regulation, described in the section on PILOT-PWI INTERPRETATION, gives examples of when right-of-way exists and what maneuvers are to be made by each aircraft under certain circumstances. However, ultimate avoidance responsibility is fixed to one of the aircraft involved (which one is not stated) and admonishes the pilot to "not pass over, under, or ahead of it [the other aircraft], unless well clear." The criterion involved here is not stated in quantifiable terms and how one goes about the appropriate maneuver(s) is not immediately clear since the whole process is left to individual construction. That is doubtless the reason why traffic gets all mixed up once in awhile, because each pilot exercises his own discretion and judgment and they choose conflicting strategies.

Mathematical analyses of avoidance maneuvers (3, 34) have led some authors to the conclusion that the best maneuvers out of the collision plane were those in which both aircraft made comparable maneuvers. Others (24) postulate a complete maneuver strategy based on altitude evasion alone. While perhaps feasible for an automated CAS, altitude evasions may rely too heavily on the pilot's ability to judge relative altitude. Also, there is somewhat of an impression in the minds of some judges who believe that aviators, in general, are prone to select turning maneuvers in preference to power changes and/or altitude changes whenever they have to execute some evasive maneuver. In particular, pilots were thought to shun maneuvers requiring strong negative g (as in a push over into a dive). The analyses mentioned earlier in this paragraph were carried out mathematically and the assumptions were not based in any way upon data on what real pilots do in such situations. In order to obtain data on this, the director of this project devised an experiment wherein aircraft photographs were shown to pilots in a simulated flight setting in such a way that collision appeared almost certain. The experimentation itself was done at NAFEC. Aircraft were seen to be approaching from sides, above, below, and head-on at distances from which escape would require almost simple reflex control wheel snatches or shoves, or rudder pedalling. The intent was to reduce the situation to a panic reaction and see what pilots would do; pull up, push over, turn, etc. The results were that the initial evasive measure was invariably a turn away from the intruder regardless of the intruder's heading. (Such a turn may <u>cause</u> a collision. A turn toward the intruder will allow the protected aircraft to pass behind the intruder in many instances.) Many more turn maneuvers were used than were altitude change maneuvers. When altitude changes were chosen it was almost always down (negative g) except where the intruder was seen to be diving, whereupon the protected aircraft was always thrown into a climb as the evasive maneuver. (19)

The output of the PILOT MANEUVER function actually forms a closed loop with the entire system. Changes in the pilot's flight path feed back into the environment and change the geometry of the target variables with respect to the protected aircraft. These changes are noted by the pilot through either the PILOT TARGET INTERPRETATION or PILOT-PWI INTERPRETATION functions and affect his evaluation and maneuver decisions. It is quite possible, therefore, for a pilot to halt or even reverse his maneuver control, depending on the results he is getting.

SECTION III

SYNTHESIS OF PILOT-PWI SYSTEMS

In the preceding chapter a number of functions were described which can be combined to form PWI systems. In that chapter it was indicated that each of these functions was related to other functions but the totality of the connections was not made evident. Constructive lessons might be learned by permuting the PWI and pilot functions described to form basic PWI system structures. Then, by varying the characteristics of each function within a given structure a large number of alternate systems possessing different attributes, may be generated. An example of this process will be described in this section. In order to preserve some semblance of order as these systems are produced, a scheme has been devised to classify the systems according to their basic structure. Three general structural categories are defined herein. These three categories cover the spectrum of pilot-PWI collision prevention systems in the broadest sense. They are: Pilot-Only, Visual Aid, and Visual Substitute Systems. Brief definitions are listed below, followed by further details throughout this chapter.

Category I - Pilot-Only Systems: In systems of this category the pilot is the <u>only</u> component of the system. Variations in search techniques, decision criteria, and maneuver logic on the part of the pilot forms the basis for generating different systems in this category. The present unaided "see-and-avoid" concept falls under this category.

Category II - Visual Aid Systems: The bulk of PWI systems fall into this category. They are characterized by having hardware which, by various means, detects targets and brings them to the attention of the pilot, who contemplates them before any threat decisions and reaction choices can be made.

Category III - Visual Substitute Systems: This category includes all PWI systems which detect targets and present enough information on the target to the pilot to enable him to make threat evaluations and maneuver decisions based on the PWI information alone, i.e., without the necessity to see the actual intruder.

These three categories cover the gamut of PWI systems from those with no hardware at all to systems one step below a fully automated CAS. One reason for such broad coverage is to show how an evaluation and comparison of the relative effectiveness of all varieties of systems between the two extreme ends of the scale could be made. This is the first step toward the construction of a PWI rating scale extending from the present-day "pilot only" situation to the more exotic "cockpit only" display that might possibly be made.

Each category of pilot-PWI collision prevention system is described in some detail below. The block diagrams of the parent systems include the pilot and PWI functions of use within that category of systems. However, all the individual systems which are sub-members of any particular category need not have the same complement of functions as the parent system.

A. CATEGORY I - PILOT-ONLY SYSTEMS

These systems have been specified to demonstrate, firstly, the baseline of performance that can be expected from the present "no hardware" systems; and secondly, to show how to determine what magnitude and variety of performance increases may be expected from such "low cost" improvements as changes in pilot training or pilot selection. At the very least, an evaluation of this category of systems will produce a better understanding of the pilot's role in collision prevention.

The basic structure of Category 1 systems is illustrated in Figure 27. The pilot's scan vector, $\vec{E}$, is generated by the PILOT SEARCH function and combined in the PILOT DETECTION function with the target position vector, $\vec{T}$, target size and luminance, and the visibility conditions from the environment. The target range and angular position of the pilot's foveal axis, δ, are computed and compared with the probability of detection curves. If the detection probability associated with the target parameters exceeds a preset value, a detection occurs. More than one target may be detected at a given instant of time, thus the integers at the output of the PILOT DETECTION function indicate the number of targets detected at that instant. The feedback loop from the PILOT DETECTION function to the PILOT SEARCH function represents the "lock-on" characteristics of the pilot's search pattern upon detection of a target. The actual target parameters are fed into the PILOT TARGET INTERPRETATION function; range, R_t, and range rate, $\dot{R}_t$, are shown here as examples. The output of this function, the information perceived by the pilot, is fed to the PILOT THREAT EVALUATION function where the threat decision is made. In Figure 27 the perceived information is denoted by the superscripts PT for Pilot-Target. The output of the PILOT THREAT EVALUATION function may be either the "no maneuver" decision in which case a feedback loop to the PILOT SEARCH function returns the pilot to his normal scanning, or it may be the "maneuver" decision accompanied by the pertinent target information that is fed directly to the maneuver logic of the PILOT MANEUVER function. The output of the PILOT MANEUVER function alters the flight path of the pilot's own aircraft and consequently changes his perspective of the target. This is indicated by the feedback loop to the target in the environment. The direct result of this is the alteration of the target position vector, $\vec{T}$.

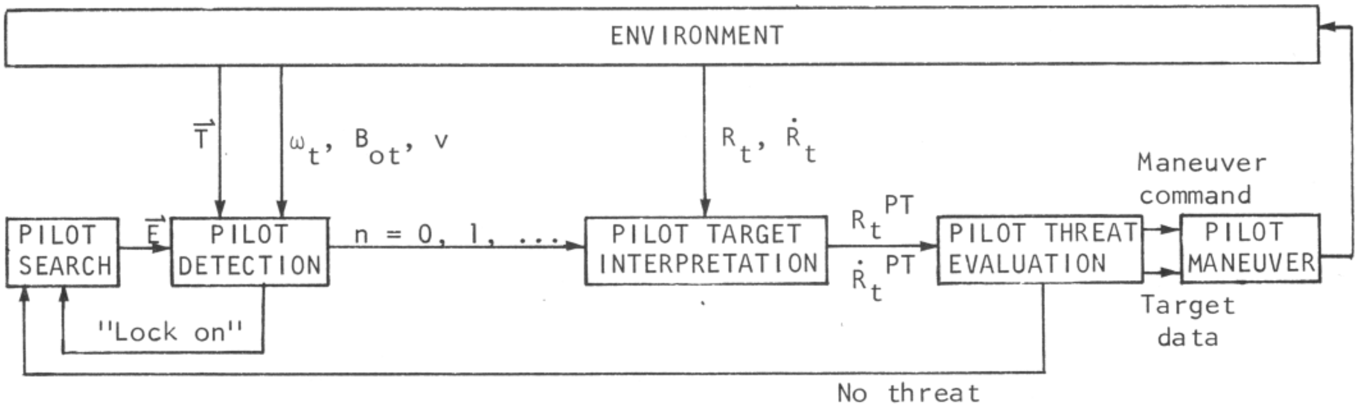


Figure 27. Category 1 - Pilot Only Systems

Each function within the system presents a potential location for deliberately varying the system characteristics and thereby generating new and different generic systems. The logical interrelation between adjacent functions, however, limits to some degree the number of sensible combinations of characteristics. For example, the decision criterion links the data required from the PILOT TARGET INTERPRETATION function to the internal processes of the PILOT THREAT EVALUATION function. The detection characteristics of the PILOT DETECTION function are partly inherent physical attributes of the pilot's visual system and partly his knowledge, training, and experience. Some of these can be changed and some cannot be voluntarily changed to generate new systems. (One possible source of variation in this function that is often tried, is in the area of target conspicuity enhancement by painting the exterior of the aircraft in various ways. However, experiments in this area show only marginal increases in detection. (45) Exterior lights, on the other hand, are clearly effective.) Major changes in the overall target detection process can be effected, however, by altering the characteristics of the PILOT SEARCH function, for the position of the target in the visual field is the most critical factor in detection.

The remaining function, PILOT MANEUVER, is characterized by the maneuver strategy and its associated logic. As mentioned earlier in this report, maneuver strategy is often related to the decision criterion. It may be treated independently, however, particularly if it is an open loop strategy. In such cases, the pilot, in response to a threat, executes a complete maneuver such as a 90° right turn or 1000-foot dive and, once commenced, the whole maneuver is carried through without modification. In many cases the pilot may be forced into an open loop maneuver since the maneuver itself occludes the target from view as, for example, when a climbing right turn in a low winged aircraft causes the pilot to lose sight of his opposing traffic. This type of maneuver differs from the closed loop maneuver in which it is possible for the pilot to visually track the target during the maneuver and continue with the maneuver only until his threat decision criterion classifies the target as a non-threat.

The net result of the above discussion is the demonstration that it is possible to reduce the number of sources for variation in performance-determining system characteristics to only three main, independent, focal issues: the search characteristics within the PILOT SEARCH function, the decision criteria used in the PILOT THREAT EVALUATION function, and the maneuver strategies exercised in the PILOT MANEUVER function. Thus, a great deal of progress may be achieved in the generation of systems under Category I if the features of that kind of PWI system are represented by a three-dimensional matrix with search characteristics along one axis, decision criteria along another axis, and maneuver strategies along a third. If S is the number of search schemes; D, the number of decision criteria; and M, the number of maneuver strategies, then SxDxM systems can be generated.

There is a large number of possible individual habits and practices in searching for targets. This large variety of search characteristics could, quite easily, skyrocket the number of possible Category I systems into astronomical proportions. Obviously, the full power of an analytic approach can be utilized only by proceeding in an unconstrained manner not only to consider what pilots <u>are</u> doing, but to probe into the areas of what they <u>should</u> be doing. To proceed with this exorbitant disregard of reality would be absurd. Accordingly, a selection should be made, on as rational a basis as is possible, of the smaller number of possibilities that are likely to be productive and instructive. One step toward keeping the number of potential Category I systems down to a reasonable level is by studying only a small variety of actual and hypothetical scan patterns with the objective of obtaining clues to definition of an optimal search procedure. The following rationale may aid in selecting reasonable search plans.

In an analytic simulation, collision threats can be caused to approach the protected aircraft on a mathematical basis, from any direction, by simply adjusting the airspeed ratio of the two aircraft involved. The greatest closing velocity for a given airspeed ratio exists in the case where both aircraft velocities summate as in the head-on collision. Since this gives the pilot of the protected aircraft the least amount of time to react between his detection of the target and the time of collision, a head-on threat is often stated to be the most critical case. A very substantial argument can be made for other kinds of collisions that can be of at least equal probability and, therefore, of at least equal importance. Situations where aircraft are drifting together abeam or pancaking atop one another, while possessing the slowest closing velocity are, unfortunately, frequent occurrences in accident statistics and suggest that occasional visual searches should be carried out along orthogonal axes to the aircraft's flight path. (Skilled aviators usually make minor clearing turns now and then so they can look below, beside and behind themselves while they are in a traffic pattern (especially at uncontrolled airports) in order to reassure themselves that they are not "flying formation" with another aircraft also in the pattern but operating in a blind spot). Thus, the criteria begins to be evident that acceptable search schemes should cover the entire sphere surrounding the protected aircraft at some not too infrequent rate and with some sort of weighted probability during the search so that the area immediately in front of the pilot is covered at a considerably higher rate.

Some of the decision criteria available to the pilot have been discussed under PILOT-PWI INTERPRETATION. While they are by no means all the possible criteria the pilot can use, they are representative of those most frequently employed. They are listed here for reference:

a. Target position and closing velocity
b. Range
c. Trajectory prediction
d. Constant relative bearing angle
e. Constant relative bearing angle and closing range
f. Tau
g. Tau with range guard.

The open loop maneuver strategies can also be summarized under three major headings (closed loop strategies are subsumed under these categories):

a. Horizontal maneuvers (turns and skids, if flying straight; rollouts, slips and skids, if flying in a turn).
b. Vertical maneuvers (climb or dive, if flying level; climb or dive further or level off, if already in ascent or descent).

c. Speed change. This is generally disdained by most pilots but it does occur occasionally. It is usually not fast enough to produce the desired results on a timely basis. (This is strange because automobile drivers often "race" with each other for the right of way. For some reason, aviators do not often seek to use speed as a collision avoidance strategy.)

With merely the examples cited here of the permutations of search, detection, and maneuver strategies (and assuming four or five types of scanning patterns) the number of distinct Pilot-only systems that can be generated in the Category I matrix ranges from 84 to 105 different systems. The selection of the "best system" from among these alone through an individual evaluation process, based on methodical cut and try research and experimentation, would be a monumental task.

Therefore, the question arises whether the selection task of making the "best system" might be brought within manageable limits by optimizing each characteristic axis of the matrix <u>independently</u> and then creating a system possessing the combination of optimum characteristics. Before this question can be answered, the term "optimal" must be defined. Without attempting to develop a value system or cost function at the present time, suppose the following elementary system objectives were offered as a definition of the sense in which a Pilot-PWI collision prevention system may be considered "optimal":

a. The system must act to effectively preclude the possibility of mid-air collision.
b. The system must avoid requirements for execution of unnecessary maneuvers or violent maneuvers.
c. The system must not make unnecessary demands upon the pilot which will detract from his other duties.

Although no economically feasible system may be able to comply completely with these objectives, they do represent, in part, the goals toward which each system should strive and against which each system may be compared. (The relevance of other such optimization criteria as necessity for training, dollar cost of ownership, human capability variations, etc., is fully recognized. However, the burden of the discussion can be illustrated with just the three criteria listed.)

In reference to the Category I, Pilot-only system, optimizing each axis independently would not appear to violate the first objective since the effective prevention of collisions would require an unfailing detection of all targets, a consistently accurate recognition of threat conditions while still controlling the aircraft, and the safe execution of avoidance maneuvers. It is apparent, however, that this practice of simultaneous optimization would not satisfy the second and third objectives. The avoidance of uneccessary maneuvers or violent maneuvers carries the necessity to avoid late target detections. This implies the necessity for early detection <u>and</u> early decision. A correct early decision cannot be made based upon threshold level detection data. (That this actually does happen is known from an experimental study.(9)) The pilot may become preoccupied with making threat decisions and numerous unnecessary maneuvers while the target is still far off in the distance. This needless process detracts from his other cockpit duties. Likewise, as is evident, the accuracy of the threat decision increases as the range to the target decreases. The most certain judgment about the likelihood of a collision thus occurs one millisecond before the event occurs, or fails to occur. This is hardly "optimal" timing. The time at which the most accurate threat decision criteria is satisfied may not necessarily allow sufficient time for a safe maneuver or a non-violent maneuver.

The resolution of these suboptimization problems is rather straightforward. Each axis of the matrix <u>can</u> be optimized; however, it must be done in a <u>specific order</u>. In this situation, maneuvers should be optimized first, followed by the decision criteria, and finally the search patterns. The results of one optimization set the constraints for the optimization of the next characteristic. That is, optimizing the characteristics of the avoidance maneuver determines the time by which the final threat decision must be made, namely, the time at which the avoidance maneuver must begin. Working backwards from this time, the optimally accurate decision criterion can be found which, in turn, sets the latest time at which the target can be detected. Since the latest time of target detection is related to the target range, an optimal search pattern can be formulated to guarantee detection of the target at the time it reaches this range. Although expressed in considerably oversimplified terms, that is how one might proceed to determine the functional specifications to be sought in a PWI system. It is not the way PWI work is being done at present.

In the following discussion the same arguments on optimization hold true for the Category II and Category III systems, the difference being the greater variety of techniques available to the pilot through the use of the PWI and the subsequent possibility of developing systems more optimal than those of Category I.

B. CATEGORY II - VISUAL AID SYSTEMS

All PWI systems which are currently being developed fall within this category. That is, all systems to date have focused on aiding the pilot in the detection of other aircraft. The aid has come from detecting targets at a greater distance or in bringing a fairly close-in target to the pilot's attention. The idea of early warning may be a mixed blessing. The earlier a target is detected the more likely the pilot will be able to avoid collision. This has been shown (9) to be true in experiments; however, early detection also leads to many unnecessary maneuvers since pilots are not able to make definite threat evaluations of targets at long ranges. In addition, long periods spent in threat evaluation may detract from other critical tasks of the pilot and contribute to pilot fatique. In this study, then, systems included under Category II will also be made to supply the pilot with additional information on targets to aid him in the evaluation of the threat. This would generally be information that the pilot is unable to obtain directly from the target himself, or critical information the pilot is unable to estimate accurately.

A general block diagram of Category II systems is shown in Figure 28. Essentially, it consists of the basic Category I system with a parallel PWI structure and the necessary interfacing functions. The existence of the

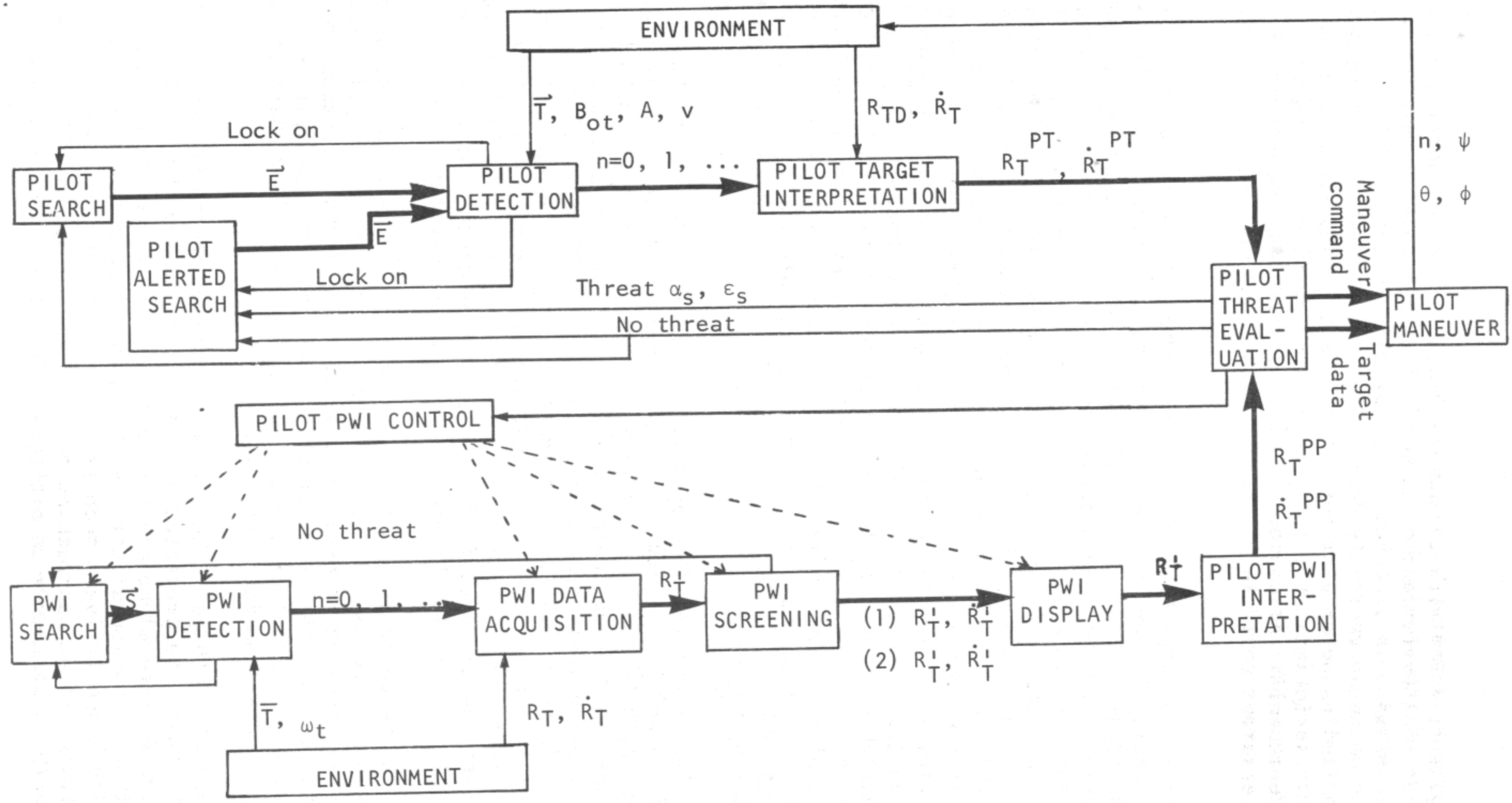


Figure 28. Category II - Visual Aid Systems

basic Category I system with the normal PILOT SEARCH function allows consideration of the development of simplified Category II systems in which the hardware serves only as a backup to the pilot's target detection duties. Such systems could be variously designed. For example, they could possess either a limited range or a higher order screening process in order to respond only to serious threats the pilot has overlooked. A wide variety of PWI hardware capabilities could be created and various amounts of man-machine interaction could be induced or avoided, depending upon individual choice.

Referring to Figure 28, it will be seen that the PWI's scan axis vector, $\vec{S}$, is generated by the PWI SEARCH function. Combining $\vec{S}$ and $\vec{T}$, the target position vector, in the PWI DETECTION function and computing the probability of detection from their angular difference, the target conspicuity, and other environmental factors, a detection occurs if this computed probability exceeds a preset value. The integers on the output of PWI DETECTION indicate the number of targets detected. The actual target data is fed into the PWI DATA ACQUISITION function and is transformed according to the system characteristics into the format specified in the system description. In Figure 28, R_t, the target range, and $\dot{R}_t$, the range rate, are given as examples of typical target data (other data could be used). R_t' and $\dot{R}_t'$ are the transformed variables appearing at the output of the PWI DATA ACQUISITION function. The data on the targets are fed into the PWI SCREENING function where they receive a preliminary evaluation and are possibly ranked in order of threat. The data which pass the screening tests are presented to the pilot via the PWI DISPLAY function. The data in the display format are denoted by the double prime; R_t'' and $\dot{R}_t''$.

The pilot receives the displayed variables, R_t'' and $\dot{R}_t''$, through the PILOT-PWI INTERPRETATION function and converts them to the perceived PWI display data, R_t^{PP} and $\dot{R}_t^{PP}$, (PP for Pilot - PWI). The PILOT ALERTED SEARCH function has been added to the basic pilot functions to permit information received from the PWI and processed by the PILOT THREAT EVALUATION function to direct and intensify the pilot's search for the target. The boundaries of the pilot's intensified search are indicated by the azimuth and elevation ranges, α_s and ε_s, which are sent to the PILOT ALERTED SEARCH function along with the search command itself. The remainder of the Category II systems structure is similar to the Category I systems structure.

As with the Category I systems, each function possesses characteristics which, when altered, would produce a new generic system. Again, the logical interplay between the functions and their characteristics reduce to a smaller number the significant characteristics that generate new systems. Seven major characteristics are cited here, although many more minor characteristics could be used to generate additional variations.

(1) Search Field Shape - The volume scanned by the PWI sensors in the space surrounding the protected aircraft is called the search field. The shape of this volume plays a major role in determining the number and type of collision situations that will be detected. Directed beams or lobes can selectively scan far in front of the protected aircraft to search for fast approaching head on encounters. Flat coin-shaped patterns select only co-altitude aircraft and eliminate many needless

alarms. While the list of possible search volumes is long, four have been selected as illustrative patterns.

a. spherical
b. forward scanning conical
c. rear hemisphere scan
d. flat ellipsoid

(2) Range - Detection range is the second characteristic of detection which selectively limits the number of targets detected. It is directly related to the design rationale of the system, that is, whether the system is to provide the pilot with advanced warning of approaching targets or alert him to targets which have already approached too close. Rather than specify numerical ranges at this time, several representative range classes are listed below relative to the pilot's maximum visual detection range (MVDR).

a. greater than MVDR
b. equal to MVDR
c. less than MVDR
d. much less than MVDR

(3) Target Screening - In those systems requiring a higher degree of target filtering than is available from search field or range control, the use of a screening function will serve this need. This characteristic is not altogether independent of the characteristics of the PWI DATA ACQUISITION function for obviously certain target information is needed before the target can be screened on the basis of such data. In the list of possible screening criteria given below, the first item, no screening, accounts for those systems which bypass this function.

a. no screening
b. relative altitude gate
c. closing range rate gate
d. Tau gate
e. Tau and range gate
f. constant bearing angle gate

(4) Target Resolution - This characteristic specifies the resolution with which the position of the target is presented to the pilot. The resolution may be limited by the type of PWI sensor being used or by the decision to reduce the target resolution at the PWI display. Five degrees of resolution are listed to illustrate the several levels of possibilities.

a. target is within the search field
b. target is within a given hemisphere
c. target is within a particular quadrant
d. target is within a specific solid angle (e.g. 30°)
e. target location in azimuth and elevation (e.g. to within 1°)

(5) Target Information - To aid the pilot in threat evaluation, additional target information may be provided in some systems. The source of this information would either be internally derived from sensor data or received from the target itself as in a cooperative system. The seven items below are only a partial list of possible target data. The first item, target exists, represents the system which does not provide the pilot with any additional information.

a. target exists
b. range
c. range rate
d. relative bearing angle rate
e. relative altitude
f. relative heading
g. target's intended maneuver

(6) Decision Criteria - This characteristic establishes the pilot's role in the system. The list of possible criteria include those listed in the Category I systems; however, with the aid of the information supplied by the PWI, many of these criteria can be used with much greater accuracy and reliability than has been previously possible in Pilot-only systems. If a given criterion is used in conjunction with PWI information, then the target information characteristics cited above are no longer completely independent characteristics and must correspond to the data requirements of the decision criterion.

a. target position and closing velocity
b. range
c. trajectory prediction
d. constant relative bearing angle
e. constant relative bearing angle and closing range
f. Tau
g. Tau with a range guard

(7) Maneuver Strategy - The control actions taken by the pilot in the event of a threatening situation can again be classified into three general categories. PWI information can also be used here for closed loop maneuvers.

a. horizontal maneuvers
b. vertical maneuvers
c. speed change

Using the characteristics listed above, Category II systems can be generated by a seven-dimensional matrix. Just including the specific examples that were listed under each characteristic, the number of different systems contained in this seven-dimensional matrix reaches beyond 70,000. The amount of interdependence between characteristics may reduce the number of systems by a few thousand. In any case, the selection of the best system is a formidable task even with a sequential optimization process, as described under Category I - Pilot-only systems. At first consideration it appears impossible to do this on a national basis.

The general optimization technique proposed for the Category II systems is illustrated in Figure 29. The first step, optimizing the maneuver strategy, determines the latest time at which a threat decision will be allowed to be made; however, in this instance there is a larger number of available strategies, including the closed loop strategies, based on PWI information. Optimizing the threat decision to provide the greatest speed and accuracy in evaluating threats also benefits from the increased variety and refinement of techniques made possible by the information supplied by the PWI.

The greatest gains in reducing the encroachment of collision detection time on the time the pilot spends attending to other duties, as well as improving the probability of timely detection, can be brought about by reducing the search time needed to detect other targets. Category II systems have the potential to meet this objective in three ways. First, by improving the speed and accuracy of the threat evaluation and avoidance maneuver, the minimum safe range of the target is reduced, thus making the target more detectable. Second, the information provided by the PWI localizes the search area for the pilot and consequently reduces the scanning time. Finally, the screening process of the PWI alerts the pilot only to those targets that are of concern, thereby reducing the requirements for outside-the-cockpit glances. The guidelines, then, for optimizing the target resolution and target information characteristics of the PWI are that these characteristics must optimize the pilot's detection and evaluation of the target. In other words, they cannot be optimized per se but must be optimized in conjunction with the effect they have on the pilot. In most PWI systems currently under development, this interaction effect is receiving very little consideration and developers are concentrating more upon the improvement of PWI hardware detection capabilities.

The minimum safe range required for detection by the PWI dominates the optimization of the search field shape, range, and screening characteristics. These characteristics must be optimized to insure the complete detection of all possible threats and the accurate filtering of those which are not immediate threats, all of this prior to the point at which the targets enter the minimum safe detection range.

The optimization of the Category II systems in this sequential manner would prevent a suboptimization of the systems while, at the same time, reducing the number of systems that need to be investigated. However, because of the sheer complexity of the PWI-pilot interactions, the optimization process itself still remains an arduous task. The computer simulation described later in this study is predicted to be of considerable use in this respect by materially reducing the manual labor involved in a direct hardware testing scheme.

C. CATEGORY III - VISUAL SUBSTITUTE SYSTEMS

The final category of PWI systems is a group of systems seldom mentioned in the discussion of PWI systems. This class of systems would provide the pilot with sufficient information on the threat in order to evaluate the situation and take the necessary actions to avoid a collision without the pilot visually acquiring the target himself. Such systems border closely on a Collision Avoidance System which detects, evaluates, and maneuvers or

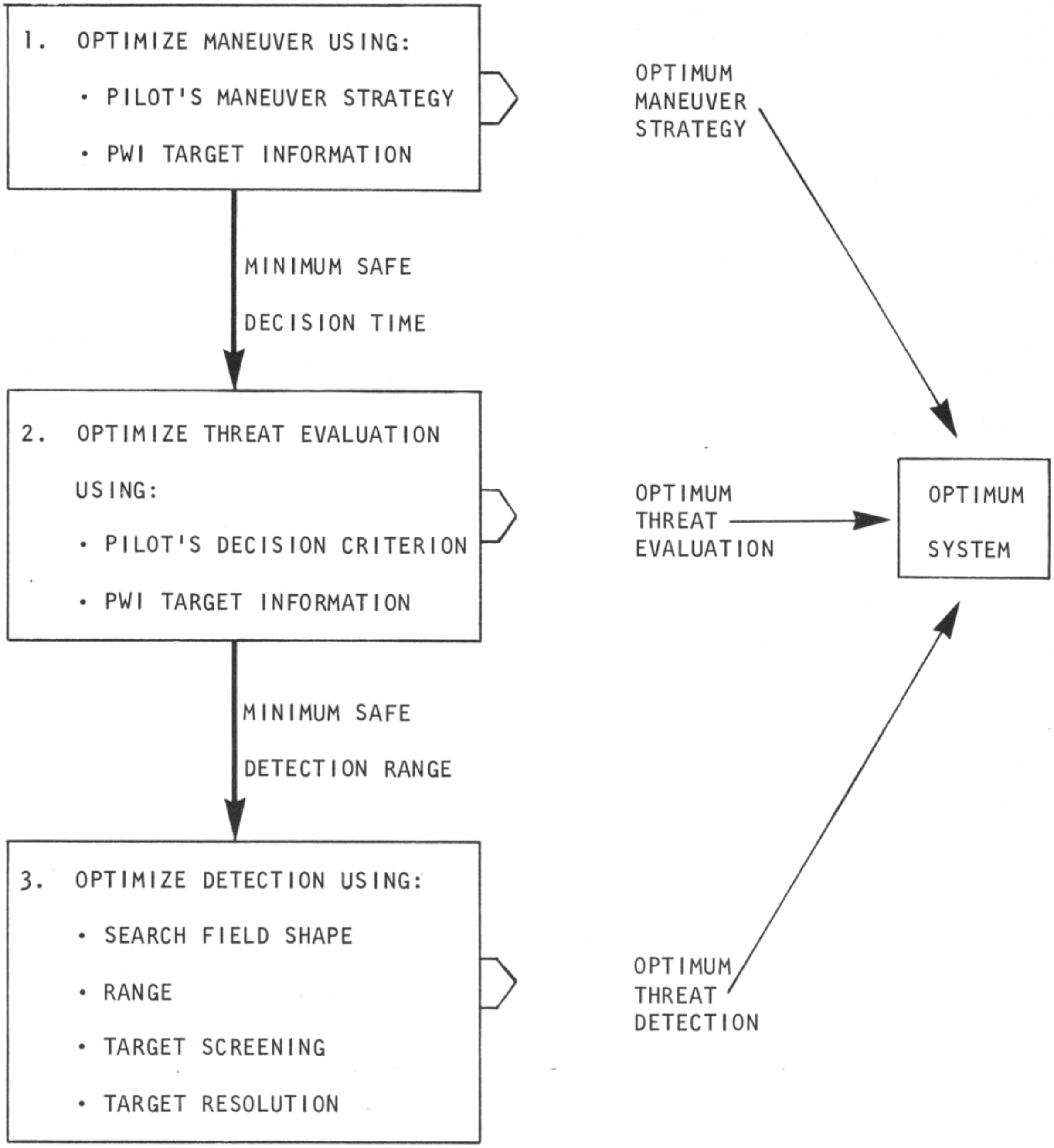


Figure 29. Category II Optimization

indicates a maneuver to the pilot completely automatically. Certainly, if a system can provide the pilot with enough information to make a threat decision without having to see the threat itself, it is but a relatively short step to wire in the decision logic for the maneuver strategy, or to address the necessary guidance right into the autopilot. However, for Category III systems as conceived herein, the final threat and maneuver decisions are caused to remain with the pilot.

Although self-contained systems of this category may, at this time, be technologically impractical and economically untenable, they do offer a theoretically desirable system and PWI systems should be designed to have growth potential into Category III form. In their most expanded form they might serve as an all-weather, day-night, omnidirectional, illusion-proof PWI system.

The structure of Category III systems is shown in Figure 30. It is identical with the Category II structure with the deletion of all pilot visual functions. The pilot's only source of target information in this category is from the PWI itself. Systems in this category would possibly be used to the greatest advantage when the pilot could not visually acquire the target either because of poor visibility conditions, or because of the visual limitation imposed on him by the aircraft structure.

A large number of systems can be generated from a functional characteristic matrix similar to the Category II systems, although only a limited number of characteristic combinations would result in reasonable and successful Category III systems. The information provided by the PWI for the pilot's decision criterion and the maneuver strategy both form the nucleus of the Category III systems.

From a functional viewpoint, two different Category III systems, each at opposite ends of the complexity scale, appear plausible. The first system, a kind of crude proximity indicator, would guard against abeam, astern, and pancaking collision by warning of intrusions into that protected airspace.

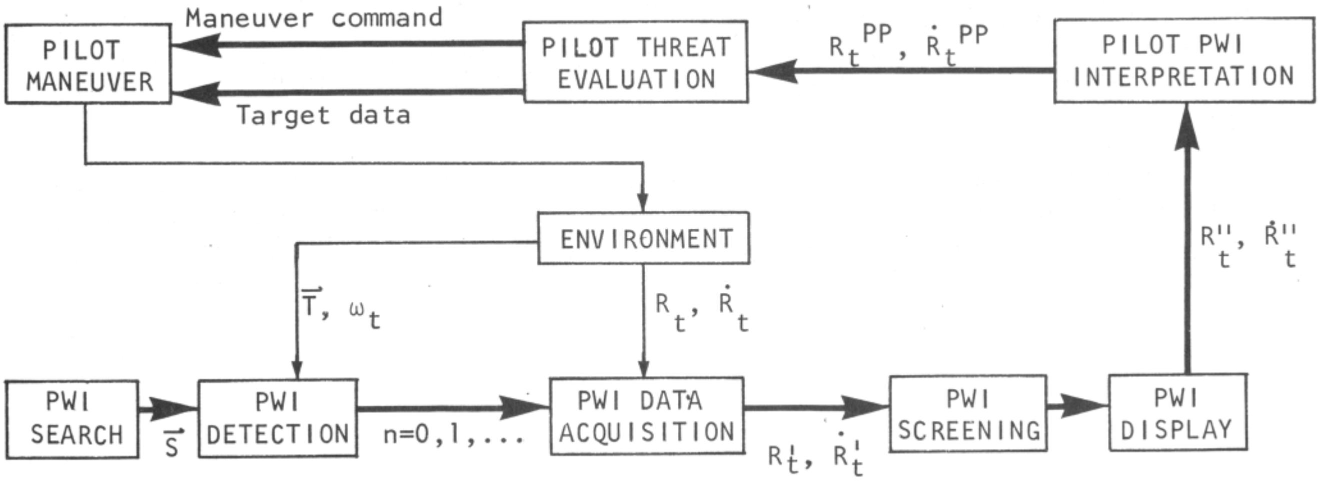


Figure 30. Category III - Visual Substitute Systems

Targets in these positions are presently shielded from view by the aircraft structure. (If there were a similar system in a Category II system it would require the pilot to maneuver his aircraft in order to see the other aircraft and then make his threat decision.) One caution is required. The range of a Category III system must be such that it gives the pilot some reasonable amount of time to determine from the PWI display in what region the overtaking aircraft is closing on him, and then to make the appropriate maneuver. Careful study of this situation is needed to insure that the maneuver the pilot makes would not, in and of itself, increase the probability of a collision. Although the slow closing velocities of the aircraft in these types of collisions are in the pilot's favor a maneuver by reference to the PWI only could be a tricky undertaking unless the display is very, very good.

The second type of useful Category III system is an advanced PWI system that could provide the pilot with complete target data at a considerable amount of time before the impending collision. Taking 1970 computational costs, the cost of onboard computation of this information would probably be prohibitive. However, the use of transmitted information, as in televised radar displays (28), may provide feasible alternatives. The success of such systems relies entirely on the presentation of accurate, precise, and comprehensive data to the pilot.

The optimization of Category III systems is again a sequential process; but in this case the pilot's target detection function is no longer needed and the process stops at the optimization of the threat evaluation. That is, only the pilot functions of display evaluation and maneuvering need be considered in optimizing the PWI characteristics.

In evaluating Category III systems, 100% detection of all threats and guaranteed safety in all maneuvers are no longer optimization objectives; they are mandatory system prerequisites. The information provided to the pilot through the PWI display must be absolutely accurate, with no possibility of ambiguity since the pilot has no other recourse. It must readily indicate the pilot's best choice of maneuvers. While these requirements are certainly important in Category II systems the instances in which the Category II systems would be used do not allow the pilot to fall back on his own visual collision avoidance skills, as he can in Category II systems. In the Category III systems the pilot must rely entirely on his only communication link with the target, the PWI, for literally all the information on which he will base his decisions.

The testing of the Category III systems for all possible collision contingencies would be an overwhelming task. One effective method of testing systems under these conditions is described in the following chapter.

SECTION IV

PROPOSED SIMULATION AND EXPERIMENTATION PROGRAM

To date, the process of development of PWI systems has originated with engineers and designers. Judging from what has been seen of their products they have generally operated somewhat as follows:

a. Get a general idea of the aircraft operational environment including the signature of intruding aircraft.
b. Create a mechanism to sense intruders.
c. Create signal management subsystems to handle sensor information.
d. Create a display to show PWI data to the pilot.
e. Show the prototype system to some pilots and see how they work with the system.

It has been observed that some developers have done better than others on the first step and have developed rather good appreciation of the atmospheric and operational circumstances within which their systems must work. Others have simply proceeded to the second step (b) with almost no consideration of (a). This second class of developer seems convinced he has a technology that will work and does not check to see if it is needed or if it applies under the prevailing constraints. A very substantial amount of development work has centered around sensor development and much of it has been directed by sponsorship which appears to be somewhat uninformed on system engineering theory or practice. As a result, enormous energies have been spent on one part of the system (the sensor) when other aspects of the system, if similarly researched, might indicate the sensor really occupies a less critical role than at first believed to be the case. One problem, of course, has been that no-one could present solid design criteria to the hardware developers. No system developer (or component developer) has devoted any real effort to information handling subsystems or to the display subsystem. It seems inconceivable that there should be such cavalier disregard for the fundamental fact that it does no good to sense something if it cannot be displayed in a form that is appropriately useful. The idea of waiting until the end of development to test an idea seems particularly ill-conceived in this contemporary age of simulation and experimentation.

In this chapter the immediate adoption of a comprehensive research and development program is advocated in order to obtain the necessary data to guide PWI development. Freedom to a limited number of others to use the old-fashioned "build-it-and-see-if-it-works" approach should be granted; in fact some developers should follow that approach since it will doubtless turn up useful data. For most purposes, however, it seems more profitable to adopt the program advocated below.

The foregoing sections of this study serve to suggest the true complexity of PWI-pilot systems and to substantiate the exception degree of interrelationships between man and machine in these systems. The operations of the total system (detection, evaluation and maneuvering) are not amenable to simple expression in a closed analytical form. This is mainly due to the interaction between the pilot and the PWI. Even if a closed mathematical form were found it would not be soluble by manual techniques.

The functional analysis conducted in Chapter 3 has identified the elements involved in the working of a PWI system and brings order and organization to this complex situation through the use of models. This study has done little to develop specific numerical values for the optional PWI characteristics. Obtaining a neat, orderly list of the characteristics and acceptable tolerances for each in terms of range, frequency, wavelength, size, etc., has been a primary preoccupation of the sponsor who wishes to pass these data along to industry. After extensive consideration, it is respectfully submitted that the achievement of the final goal, the quantitative specification of PWI characteristics, is beyond the scope of the present study. Preparation of specifications must await general system design and that, in turn, has to depend upon three things: 1) execution of a functional analysis to explore how things might best be organized, what elements and links might be performed within the system, and what relationships might prevail under probable operational circumstances; 2) data on the performance capabilities and limitations of various human and machine characteristics accumulated as evidence or data from parametric studies, experiments, simulations, and demonstrations of various PWI configurations operated within anticipated constraints. Preparation of prospective specifications lies properly in the realm of system simulation and evaluation where the necessary number and variety of hypothetical collision courses can be run using realistic numerical values for the parameters involved.

The discussion on system optimization at the end of the preceding chapter (3) suggests a method of optimizing segments of the total PWI system through taking variables one at a time in sequential order and exercising them throughout the limits of their occurrence while systematically controlling other variables, including holding each other variable at its optimal value. However, even in optimizing a small portion of the overall system, the number of environmental contingencies under which the PWI system must perform makes this task exceptionally difficult. In the early stages of testing for the optimal system, direct man-in-the-loop experimental simulations of even segments of the total system become both economically and technically impractical because of the myriad of contingencies required for a complete test. Considering the responsibility in specifying the ultimate and optimal set of PWI characteristics and interaction effects between variables, such an exhaustive testing program is needed. As a possible solution to this dilemma it is advocated that the reaction and performance of pilots in appropriate operational settings, be determined in a related series of limited experimental situations. The data from these small studies can be reconstructed into the performance of various hypothetical total systems (as outlined in the functional analysis), simulated on a computer, and run at fast time to complete a substantial number of tests in a small amount of machine time.

In addition to inductively predicting system performance based on experimental data, a computer simulation allows the pilot's behavior to be varied on a hypothetical basis and determines, in some optimal sense, what the pilot should be doing. Since a wide variety of potential pilot characteristics can be cranked in without the necessity of selecting aviators with special abilities, or to go through the lengthy business of training them to perform in certain ways, the influence of alternative pilot knowledges and skills can be speculated on. In the same manner, a particular system's performance may be tested for its sensitivity to a particular aspect of pilot behavior, also under completely hypothetical conditions, and various man-machine interactions can be explored without necessarily building physical models.

The most responsible, productive, economical, and timely approach to the generation of quantitative PWI characteristics would appear to be a coordinated program of manned experiments and computer simulations originating in the functional analysis presented in this report.

There have already been too many speculative attempts to describe PWI specifications and this practice should be stopped. A rigorous and substantial program of experimentation and simulation is advocated as the only reasonable course of action.

Conception and planning of a comprehensive manned experimental research program is a substantial undertaking, at least rivalling the present four-part contract. Accordingly, in view of funding and time limitations, it has not been possible for Rowland & Company to develop and present herein such a series of research plans to support PWI specification generation. The functional analysis described in this report provides the key areas where critical system performance would have greatest impact. For example, suggested research areas are in search strategies; influence of false alarms; influence of failure to show visible but non-threat targets; ability of the human to relate guidance from various display configurations to traffic situations; target resolution against various backgrounds; ability of the human to mentally compute tau; preferred maneuver strategies as a function of characteristics of confrontation with the intruder; acceptability of closed loop avoidance maneuvers as compared with open loop maneuvers; time parameters in threat evaluation (search, detection, etc.); circumstances leading to preferences for one decision criterion over others; how much target information is required to support the process of detection (of evaluation, of decision); effect of displaying targets approaching from regions where they cannot be seen; acceptable lower limit of near-miss in altitude (in range); inside-the-cockpit versus outside-the-cockpit time sharing requirements during various operations; ability to estimate speed change to avoid collision; comparison between daytime and nighttime collision detection (and interpretation); pilot eye movements; and numerous other such topics.

As may readily be perceived, to lay out a test plan or experimental design for each of the topics above, along with description of hypotheses, subjects, equipment, statistical and other data reduction and analysis plans, etc., is a sizeable job. In the course of the present contract, more than a dozen such experiments have been devised and passed along to the Test and Evaluation Division at NAFEC, who have been working on them as their time and equipment and staff have permitted. Some of these experiments have been completed and others are in progress.

The execution of a good number of the proposed experiments requires research equipment of significantly greater scale and sophistication than is known to exist. Rowland & Company has submitted a tentative description of the apparatus required to support the necessary research. (Most of this apparatus is also suitable for other aviation-related research, so the equipment would be amortized across other programs.) The PWI research devised and conducted under the present contract has been deliberately kept simple in order to permit it to be carried out with existing capabilities. A very much larger and more sophisticated research program is most definitely needed.

Within this chapter the connection between the functional analysis and a computer simulation is illustrated by describing the general layout of a computer simulation study which is specifically put forth as being the next most logical step in development of tentative PWI system specification.

The computer simulation, as proposed, can be put to use most effectively in three areas: 1) to generate a multitude of possible simulated collision conditions; 2) keep track of the flow of information and actions within each PWI and pilot function; and 3) score the overall system on its performance. To emphasize these three aspects of the task the computer simulation described below is divided into three areas of effort: a) scenario generation; b) system modeling; and c) system scoring.

These three areas would actually be run concurrently in the computer analysis. In order to do the simulation, the characteristics of a functional model of a given system are first entered into the computer then each environmental scenario is played through the functional model several times in a Monte Carlo fashion to score the system on a statistical basis. After the entire gamut of scenarios has been played through the system model the statistical scores, diagnostics, and general evaluations of the system are printed out. A schematic of this process is shown in Figure 31.

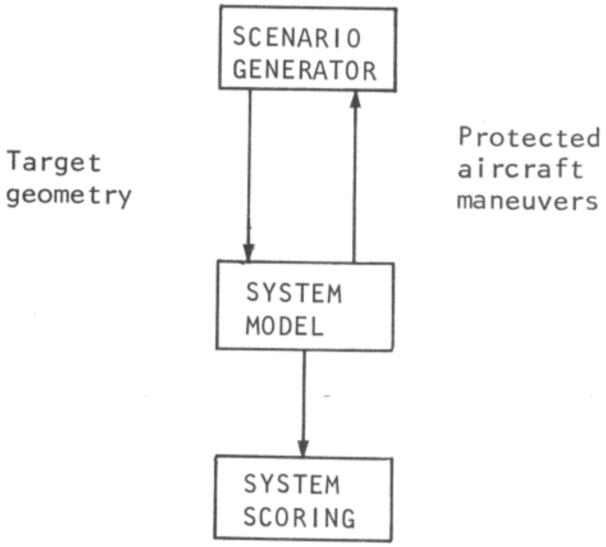


Figure 31. Computer Simulation: General Layout

A. SCENARIO GENERATION

A scenario may be broken down into the elements that contribute to the collision situation. These elements have been referred to generally in this report as "the environment," and encompass such things as visibility conditions, target characteristics, and the collision geometry. These are listed below in Table 4 along with representative numerical values:

Visibility, the first item in Table 4, is obviously a critical factor in any system requiring visual contact with the target. The 10-mile range may be considered good VFR operating conditions while the 1-mile range is the current minimum visibility condition for VFR flying in uncontrolled airspace. The 0.25-mile visibility represents a severely degraded mode of operation which would not qualify under any current version of a VFR concept. It characterizes the situation in which a pilot flying VFR inadvertently flies into IFR weather. In this case, should a collision situation arise the pilot must use whatever information on his traffic is available to him from the PWI, (assuming the PWI receives its data from some sensor not affected by the poor visibility).

Under the heading of "traffic" (Table 4) comes a variety of encounters starting with the elementary two-aircraft encounter. This simple unaccelerated encounter is aimed at testing the discriminatory power of the pilot-PWI system in separating hazardous situations from close, but safe, passes. The multiple target situations listed represent heavy traffic conditions in which the systems must be able to handle more than one threat simultaneously without generating secondary collision situations, confusing the pilot, unnecessarily elevating his anxiety level, etc.

Based upon study of typical behavior, five aircraft types have been established to generate a wide range of target sizes, closing velocities, angles of approach, and maneuverability. Approximate cruising speeds, rates of climb and sink rates have been estimated for each type (Table 4).

TABLE 4. COLLISION SITUATION ELEMENTS

Element	Typical Values				
Visibility	10 miles, 3 miles, 1 mile, 0.25 mile				
Traffic					
Number of targets	1, 2, 5				
Number of threats	0, 1, 2				
Aircraft Type					
Cruising speed (knots)	100	150	250	350	500
Maximum rate of climb (ft/min)	500	1000	1200	2500	6500
Nominal rate of descent (ft/min)	500	900	1500	2000	6500
Phase of Operation	Climbing, cruising, descending, turning, accelerating, decelerating				
Direction of Approach	Head-on, abeam, astern, above, below				

Additional information yet to be included would cover such items as lateral turning responses and luminances.

Phase of operation and direction of approach complete the specification of the initial collision geometry variables shown in Table 4. Direction of approach is not completely independent of the aircraft type, which specifies the aircraft velocity, or phase of operation, which determines the initial flight path angle.

With just two aircraft involved and assuming only one example of each variable (i.e., only one angle of climb, one direction of abeam approach, etc.), the number of potential collision situations that can be generated from the above table is over 3,000! Worse yet, the number of realizable encounters for more than two aircraft increases geometrically with the number of aircraft involved. Obviously, some practical approach to generation of the multiple target encounters must be found that differs sharply from the two-aircraft situation. Instead of producing an exhaustive list of possible encounters, the mutiple threat situations would simply have to be chosen to focus on the various types or classes of representative problems of a PWI system in such an environment. As an example, consider two widely separated targets one of which is a threat, the other is not. Will the detection of the one prevent the detection of the other or, if the non-threat is detected first, will it jeopardize the evaluation of the real threat? Further valuable scenarios include turning targets as well as curved flight paths for the protected aircraft.

In addition to presenting the initial flight paths for a particular scenario, the scenario generation package of the computer program is charged with the task of generating the geometric variables of the encounter as the situation unfolds. These variables include the target position vector, $\vec{T}$, in particular, and among other items: the range rate of each target; the angular size of each target; the attitude of each target with respect to the protected aircraft, the relative bearing angle rate, and the relative altitude of each target.

Depending on the PWI system concept being evaluated, some or all of these variables would be fed into the system model. In return, the protected aircraft maneuvers would be fed back to the scenario generator to recompute the encounterment geometry as the situation progresses.

B. SYSTEM MODELING

The computer simulation of the pilot-PWI systems follows directly from the system structures developed in the preceding chapters of this report. The simulation could be used to study the complete system or one segment of the system as might be done in the optimization process. Let us examine a way in which this simulation could be done. It should be understood that the practices described are intended to be illustrative in nature and that many other alternatives could be cited.

Each group of PWI or pilot functions in the system structure can be set up as subroutines in the computer simulation. For example, the search and detection functions of either the pilot or the PWI form one subroutine as shown in Figure 32. In the first step of the subroutine, $\vec{S}$ or $\vec{E}$, whichever is the case, would be computed for a given instant of time, t, either from a stored scan pattern table or by a stochastic process. Simultaneously, the probability of target detection would be computed from the target data received from the scenario as a function of the target's position in the scan volume, $\overrightarrow{SV}$. In the next step, $\vec{S}$ or $\vec{E}$ would be subtracted from $\vec{T}$ which has been obtained from the scenario also, and a numerical value of P_{det} would be found. Using random numbers, a test would be made on the detection of the target. If it is not detected, time would be incremented and the program returned to the search function. If the target is detected, time would be incremented by the time required for detection to occur and the subroutine would exit to the main program. Each time t is incremented the scenario would recompute all the geometrical variables for the new value of t.

For either the PWI DATA ACQUISITION or PILOT TARGET INTERPRETATION subroutines, the actual target data would be entered from the scenario routine as shown in Figure 33. This subroutine would modify the target data as described in sections PILOT DETECTION for the pilot, or PWI DATA ACQUISITION for the PWI. Once again, t would be incremented, this time by an interpretation delay. Following this, the subroutine would exit to the main program.

The PWI SCREENING subroutine would be simply a matter of testing the actual target data from the scenario for those targets that have been detected. The threat status and priority of each target would be determined and the subroutine would exit to the main routine with this information.

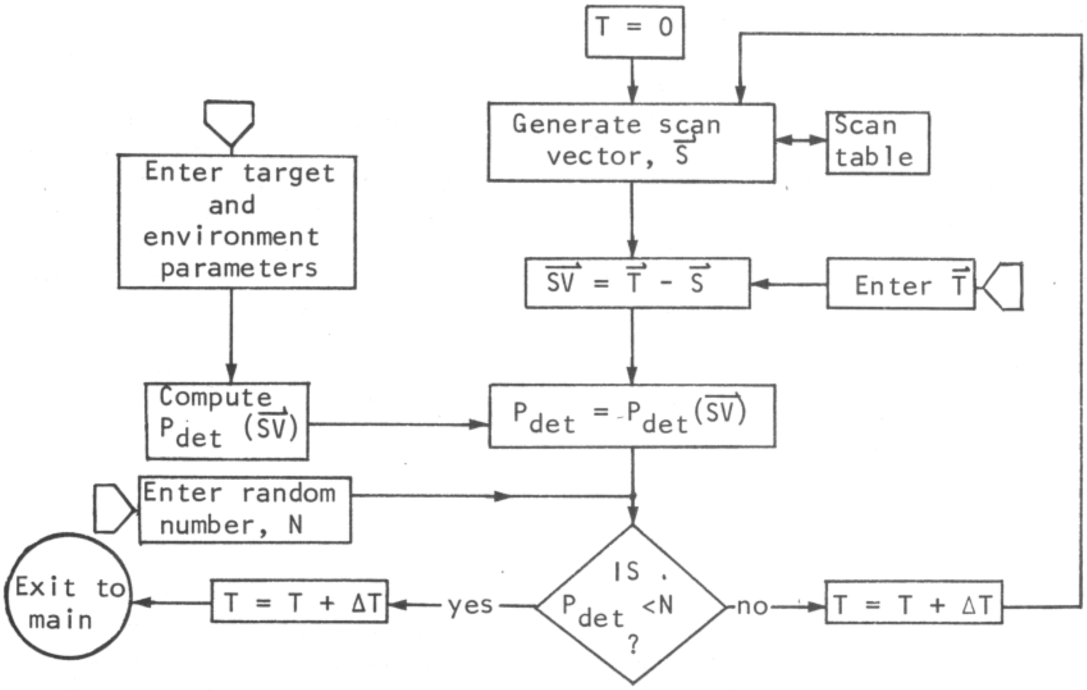


Figure 32. Detection Subroutine

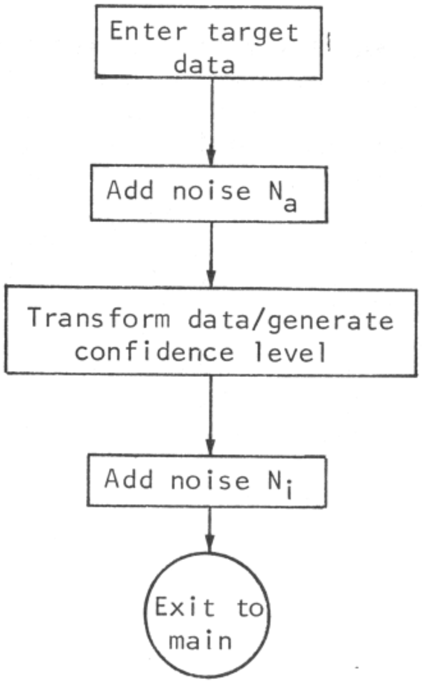


Figure 33. Data Acquisition Subroutine

The interfacing routines between the pilot and PWI portions of the model would depend largely on the system being analyzed. Each time information would jump from one to the other, however, t must be incremented to account for the pilot's reaction or interpretation time.

In the pilot segment of the model the decision criteria subroutine, as shown in Figure 34, has five outcomes, each denoting a specific course of action. The threat decisions increment t and generate a corresponding pilot maneuver command. This command would be eventually fed into the maneuver subroutine to compute the change in the protected aircraft's flight path. The certainty with which the threat is determined would dictate the severity of the maneuver command. The 'no threat' decisions would return the subroutine to the main program which would reactivate the search and detection subroutines. If a decision could not be reached, t would be incremented, the main program informed, and the data acquisition subroutines entered again as new data would be fed into the decision criterion, and the evaluation process attempted again.

C. SYSTEM SCORING

The third section of the simulation program, the scoring routines, would generate one of the end products of the entire research effort, a PWI system effectiveness rating. The printed output of this segment would reduce the events that have occurred during the multitude of scenario runs to a revealing, concise, and comprehensive format readily interpreted in light of the objectives established in Category 1 - PILOT ONLY systems.

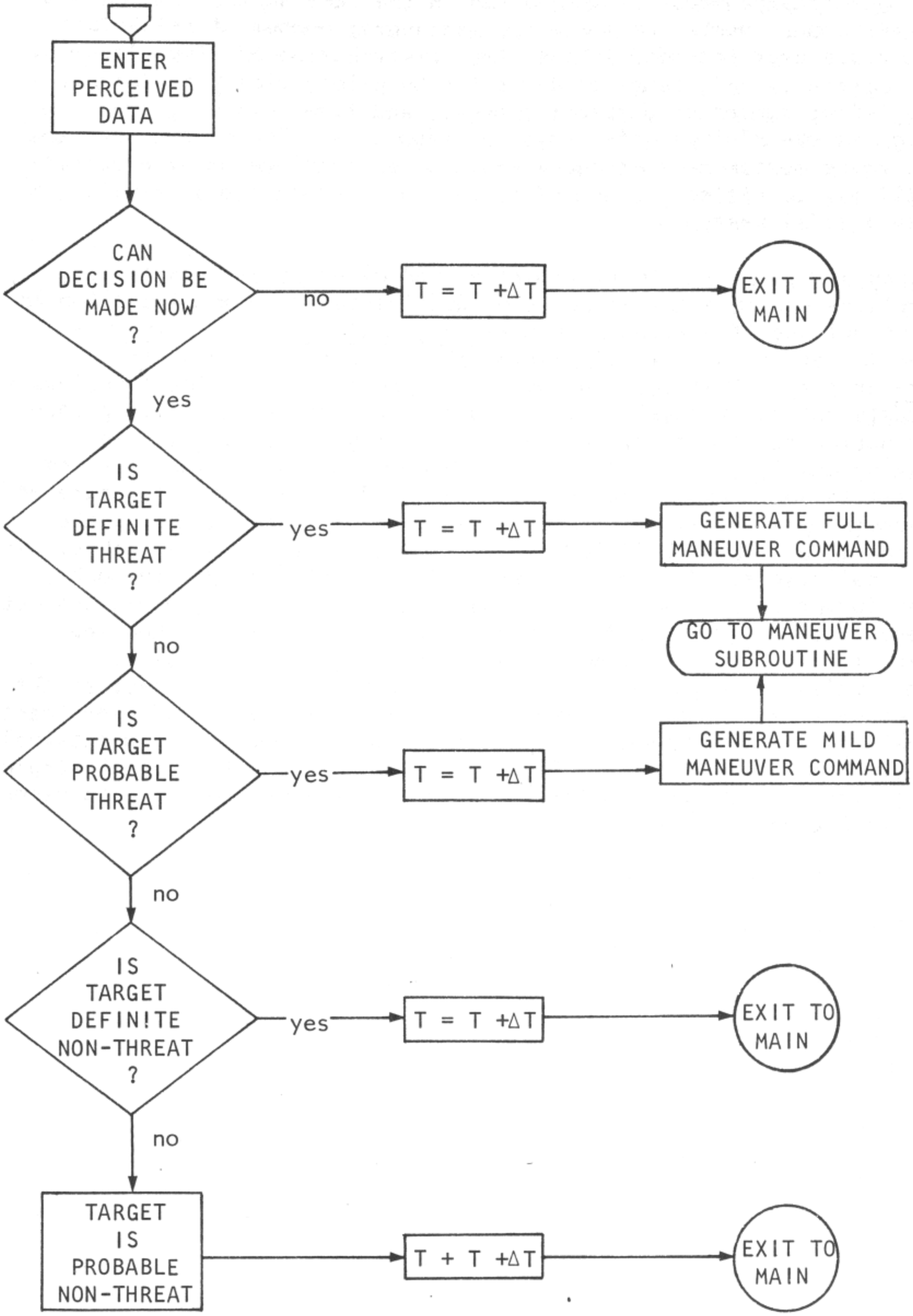


Figure 34. Threat Evaluation Subroutine

Typical performance measures documented in the scoring routine would be: number of collisions; number of necessary maneuvers; number of collisions avoided; increase over intended flight time; distribution of miss distances; range at detection by PWI; range at detection by pilot; time from detection to first decision; number of decision changes; and time remaining from the last decision to the minimum safe range decision time. For each system that is analyzed these performance measures would be categorized under aircraft types, visibility conditions, phase of operation of protected aircraft, and direction of initial approach.

This paragraph is particularly important and deserves close attention since it explains the interaction between experimentation and simulation in derivation of PWI specifications on a rational, logical, basis. The system modeling portion of the overall simulation should be perceived as an evolutionary process. That is, the model, particularly the pilot functions portion, starts out on extremely simplified assumptions: rectangular probability distribution functions; error-free data interpretation; discrete decision-making model; and step input control commands, since there is comparatively little hard data to go on. As data is found in the literature or produced through experiments and field trials of prototype equipment, the details of the model could be filled in bit by bit until a highly sophisticated, highly realistic simulation would be produced. Viewed from the other side, the evolution of the data from the simulation, in itself, would suggest the hypotheses and procedures and apparatus required for coordinated and directed experimentation. In turn, the simulation capability would provide an immediate outlet for application for the experimental data as fast as the data would be obtained in the coordinated, chain-linked program of experiment-simulation-experiment-simulation ... . As the program proceeded, successively better approximations could be made for PWI system specifications. A single hard and fast set of PWI specifications should not be expected, but improvements would occur with each iteration.

SECTION V

SUMMARY AND CONCLUSIONS

It is realistic to experience growing concern over the potential rise in mid-air collisions since the usage of the airspace is increasing at an ever accelerating pace. This concern has led to the increased investigation of techniques for preventing mid-air collisions. While the development of a Collision Avoidance System for airline transports and high performance aircraft has apparently been proceeding reasonably satisfactorily, progress on a low cost system for the general aviator has not met with the same success. These low cost systems, Pilot Warning Instruments (PWI's), are principally intended to aid the pilot in his detection and evaluation of threatening aircraft. The highly interactive relationship between the pilot and his electromechanical PWI system precludes the successful development of a PWI strictly on the basis of the hardware alone although, unfortunately, it is on the hardware side of the system that the lion's share of the research and development money has been spent to date.

To investigate the properties of the pilot-PWI relationship and to establish the role of each in the prevention of collisions, a functional analysis is made in this report. In this analysis, the specific functions of both the pilot and the PWI are identified and defined. Five functions were assigned to the PWI and eight to the pilot. In the case of the PWI functions, examples of current or possible hardware techniques for performing each function are briefly explained.

More attention was given to the description of the pilot functions; in part, because of the lack of attention paid to the pilot in the past, and in part, because of the predominance of the pilot in the achievement of collision avoidance. As a method of analyzing and describing the pilot functions, mathematical models which are partially based on empirical data were reviewed. Specifically, models for generating the pilot's search patterns and for simulating his target detection capabilities have been developed.

In extending the analysis past the detection of targets, pilot functions involving the evaluation of threats and determination of proper maneuvers were also established. Although some data on the estimation of target parameters were cited, a real need for experimental data exists on the pilot's ability to cope with the decision criteria and maneuver strategies listed under their respective functions.

The second half of the functional analysis consisted of determining the relationship between the environment, the PWI, and the pilot. The individual functions of the pilot and the PWI were connected together in a systematic fashion to form three categories of systems; pilot only systems, visual aid systems, and visual substitute systems. The first of these required no hardware to avoid collision; it is essentially typical of the present day "see-and-avoid" conditions. The second category, which included most of the present PWI design concepts, employed PWI systems which assist the pilot to detect the target with the pilot then making the threat evaluation on the basis of direct visual observation of available areas. The third category were systems which, in themselves, both detect the traffic and provide the pilot with sufficient information to make the threat decision without the necessity of actually seeing the traffic. The independent characteristics descriptive of each of these systems were listed and used to form system generating matrices. The number of independent and unique PWI systems that can be generated in this manner was shown to be so large that special techniques of elimination must be devised.

In order to select the best of these systems for a given set of circumstances, an optimization technique was proposed. This technique called for the sequential optimization of the individual characteristics beginning with the maneuver strategy, followed by the evaluation process, and finally the detection process. This optimization process was designed to maximize the effectiveness of the systems while minimizing the amount of unnecessary maneuvering and pilot distraction and pilot workload.

The final section of this study described the general layout of a computer simulation which would aid both in the evaluation of systems under a larger number of collision contingencies and in the optimization of pilot and PWI characteristics. The simulation was divided into three segments; the scenario generation, the system model, and the system scoring. The scenario generation segment produces the large number of collision contingencies needed for a complete system evaluation. It also maintains and computes the geometrical target parameters during the course of a run. The system model segment was patterned after the block diagram descriptions of the basic system categories. Each grouping of PWI and pilot functions forms a subroutine within this segment. The characteristics of the system under investigation would be entered into the appropriate subroutine. The system scoring segment was designed to monitor the performance of a system as the scenarios were played through the system in a Monte Carlo fashion. The output of the scoring routines would be a statistical description of the system's performance as a function of aircraft type involved, collision geometries, and visibility conditions.

It was noted that the simulation program would be most successful if it were to work hand-in-hand with a series of ground based and airborne experiments which would feed data and hypotheses back and forth between themselves in a singularly productive manner. Out of this series of experiments and simulations there would come an increasingly more and more accurate set of specifications which would describe, define, or otherwise identify the performance characteristics to be sought in PWI systems.

No useful purpose would be served by adding more ungrounded speculations to those already in existence and being used as specifications for PWI systems. What is needed, and badly, is a systematic, large scale research program as outlined above. Accordingly, our recommendations are:

1) Acquire suitable research facilities and equipment including realistic, research quality, multiple target, large scale air-to-air simulation devices.

2) Acquire additional professional assistance on either an in-house or contract basis.

3) Design, then conduct and evaluate an integrated series of experiments and studies which will describe behavior of pilots and PWI hardware under various conditions.

4) Using substantial computational facilities develop simulated models of PWI systems, including human contribution thereto, and exercise these models so as to derive the optimal characteristics to be sought in PWI systems.

5) Apply the derived data to prototype PWI systems developed either by the FAA or under contract.

6) Execute field tests and computer simulations and laboratory research with the prototype PWI systems making sure to include consideration of both pilot factors and mechanical factors.

7) Establish the PWI standards for the developers to aim for and for the FAA to use as acceptance test criteria.

As a kind of recommendation, yet not of the same type as those listed above, the FAA should clearly and unambiguously establish itself as the organizer and leader in the PWI development area by organizing and funding an active in-house and contract research and development program; by acting as the monitor and clearinghouse of PWI information, and by establishing specifications, standards, and test criteria. The PWI field needs leadership and the FAA should provide that leadership.

SECTION VI

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