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A Human Model Which Optimizes Pursuit Tracking.

Mario Joseph Caluda Jr
Louisiana State University and Agricultural & Mechanical College

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in

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by

Mario Joseph Caluda, Jr.
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# TABLE OF CONTENTS

ACKNOWLEDGEMENT ........................................ ii
LIST OF TABLES ............................................. v
LIST OF FIGURES .......................................... vi
ABSTRACT .................................................. ix

SECTION  

I  INTRODUCTION ........................................... 1
   Object of the Study .................................. 2
   Scope of the Investigation ......................... 4
   Summarization ....................................... 6

II  DETERMINATION OF CONCEPTS ............................ 7
   Task Determination .................................. 7
   Model Determination .................................. 9
   Performance Criteria ................................ 18

III  METHOD OF MODEL VARIATION ............................ 24
   Technique Selection Based on Previous Studies .... 24
   Technique Description ................................ 29

IV  METHODS FOR ANALYSIS .................................. 39
   Digital Analysis ...................................... 39
   Spectral Analysis .................................... 52

V  OPTIMIZATION TECHNIQUE APPLIED TO AERIAL  
   SIMULATION ........................................... 60

VI  INVESTIGATION RESULTS ................................... 74
A LIST OF TABLES

<table>
<thead>
<tr>
<th>TABLE</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Fletcher Comparisons</td>
<td>28</td>
</tr>
<tr>
<td>II</td>
<td>Box Comparisons</td>
<td>30</td>
</tr>
<tr>
<td>III</td>
<td>State-Of-The-Art Simulation Data For A Human Nulling Error By Stick Rotation</td>
<td>82</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>1</td>
<td>Self Adaptive Control Model</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>Compensatory Tracking System</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>Pursuit Tracking System</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>Range Error Criteria</td>
<td>21</td>
</tr>
<tr>
<td>5</td>
<td>Tracking Error Geometry</td>
<td>22</td>
</tr>
<tr>
<td>6</td>
<td>Reference Model Adaptive System</td>
<td>25</td>
</tr>
<tr>
<td>7</td>
<td>Steepest Descent Procedure for Two Dimensions</td>
<td>32</td>
</tr>
<tr>
<td>8</td>
<td>Minimization Stepping Procedure</td>
<td>34</td>
</tr>
<tr>
<td>9</td>
<td>Non-Gradient Optimization Procedure for Two Dimensions</td>
<td>37</td>
</tr>
<tr>
<td>10</td>
<td>IMAGE Simulations</td>
<td>40</td>
</tr>
<tr>
<td>11</td>
<td>Inneractions Between Flight Path, Terminal Effectiveness, and Fire Control</td>
<td>43</td>
</tr>
<tr>
<td>12</td>
<td>Major Portions of the Fire Control Integration Loop</td>
<td>45</td>
</tr>
<tr>
<td>13</td>
<td>Autopilot Inneraction in the Elevation Channel</td>
<td>48</td>
</tr>
<tr>
<td>14</td>
<td>Autopilot Inneraction in the Traverse Channel</td>
<td>49</td>
</tr>
<tr>
<td>15</td>
<td>Power Spectral Density Function</td>
<td>55</td>
</tr>
<tr>
<td>16</td>
<td>Cross-Correlation Function</td>
<td>56</td>
</tr>
<tr>
<td>17</td>
<td>Autocorrelation Function</td>
<td>57</td>
</tr>
<tr>
<td>18</td>
<td>Optimization Control of the Fire Control Integration Loop</td>
<td>61</td>
</tr>
<tr>
<td>19</td>
<td>Parameter Optimization Subroutine</td>
<td>64</td>
</tr>
<tr>
<td>20</td>
<td>Non-Derivative Minimization Subroutine</td>
<td>67</td>
</tr>
<tr>
<td>21</td>
<td>Relative Minimum Subroutine</td>
<td>70</td>
</tr>
<tr>
<td>Figure</td>
<td>Page</td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>------</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>Summation of Per Step Error Evaluation Subroutine 73</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>Optimum Fixed Parameters for Two-G Maneuver 75</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>Two Parameter Optimization for Two-G Maneuver 77</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>Optimum Fixed Parameters for Two-G Maneuver 79</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>Four Parameter Optimization with Lags for Two-G Maneuver 80</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>Optimum Fixed Parameter versus Four Parameter Optimization for IMAGE Case 3.01 81</td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>Four Parameter Optimization with Lags for Hassle Case 3 84</td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>Six Parameter Optimization with Lags for Hassle Case 3 85</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>Six Parameter Optimization with Lags for Hassle Case 3 87</td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>Parametric Effect for Six Parameter Optimization Utilizing Hassle Case 3 88</td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>Six Parameter Optimization with Lags for Hassle Case 3 91</td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>Parametric Effects for Six Parameter Optimization Utilizing Hassle Case 3 92</td>
<td></td>
</tr>
<tr>
<td>34</td>
<td>Six Parameter Optimization with Lags for Hassle Case 3 94</td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>Parametric Effects for Six Parameter Optimization Utilizing Hassle Case 3 95</td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>Six Parameter Optimization with Lags and Reaction Dead Time for IMAGE Case 4.02 96</td>
<td></td>
</tr>
<tr>
<td>37</td>
<td>Six Parameter Optimization with Lags and Reaction Dead Time for Hassle Case 3 97</td>
<td></td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td>------</td>
</tr>
<tr>
<td>38</td>
<td>Six Parameter Optimization with Lags and Reaction Dead Time for Hassle Case 1</td>
<td>98</td>
</tr>
<tr>
<td>39</td>
<td>Six Parameter Optimization with Lags and Reaction Dead Time for IMAGE Case 3.01</td>
<td>99</td>
</tr>
<tr>
<td>40</td>
<td>Minimum Miss Distance for Fixed Parameter versus Optimum Parameter for IMAGE Case 4.02</td>
<td>101</td>
</tr>
<tr>
<td>41</td>
<td>Parametric Effects for Six Parameter Optimization Utilizing IMAGE Case 4.02</td>
<td>102</td>
</tr>
<tr>
<td>42</td>
<td>Parametric Effects for Six Parameter Optimization Utilizing Hassle Case 3</td>
<td>103</td>
</tr>
<tr>
<td>43</td>
<td>Parametric Effects for Six Parameter Optimization Utilizing IMAGE Case 3.01</td>
<td>104</td>
</tr>
<tr>
<td>44</td>
<td>Elevation Channel for Variation of Pilot Gain Parameter</td>
<td>107</td>
</tr>
<tr>
<td>I-1</td>
<td>IMAGE Case 4.02 Horizontal Two-G Turn</td>
<td>114</td>
</tr>
<tr>
<td>I-2</td>
<td>IMAGE Case 3.01 Horizontal Non-Maneuvering Evader</td>
<td>115</td>
</tr>
<tr>
<td>I-3</td>
<td>Hassle Case 1 X-Z Plane for Attacker</td>
<td>116</td>
</tr>
<tr>
<td>I-4</td>
<td>Hassle Case 1 X-Y Plane for Attacker</td>
<td>117</td>
</tr>
<tr>
<td>I-5</td>
<td>Hassle Case 1 X-Z Plane for Evader</td>
<td>118</td>
</tr>
<tr>
<td>I-6</td>
<td>Hassle Case 1 X-Y Plane for Evader</td>
<td>119</td>
</tr>
<tr>
<td>I-7</td>
<td>Hassle Case 3 X-Z Plane for Attacker</td>
<td>120</td>
</tr>
<tr>
<td>I-8</td>
<td>Hassle Case 3 X-Y Plane for Attacker</td>
<td>121</td>
</tr>
<tr>
<td>I-9</td>
<td>Hassle Case 3 X-Z Plane for Evader</td>
<td>122</td>
</tr>
<tr>
<td>I-10</td>
<td>Hassle Case 3 X-Y Plane for Evader</td>
<td>123</td>
</tr>
<tr>
<td>I-11</td>
<td>Hassle Case 1 Three Dimensional Attacker</td>
<td>124</td>
</tr>
<tr>
<td>I-12</td>
<td>Hassle Case 1 Three Dimensional Evader</td>
<td>125</td>
</tr>
<tr>
<td>I-13</td>
<td>Hassle Case 3 Three Dimensional Attacker</td>
<td>126</td>
</tr>
<tr>
<td>I-14</td>
<td>Hassle Case 3 Three Dimensional Evader</td>
<td>127</td>
</tr>
</tbody>
</table>
ABSTRACT

The feasibility of using an adaptive linear mathematical model to represent a human operator subjected to the task of controlling an attacking fighter aircraft was investigated. The ability of the model to perform pursuit tracking tasks subject to random evader tactics was analyzed by the implementation of the model into a six-degree-of-freedom digital fire control simulation. For the model to approach reality in every flight regime, an adaptive procedure was incorporated into the simulation to adjust the variable gain and lead time parameters of the human model. The adaptive procedure which uses a six parameter optimization scheme similar to that developed by M. J. D. Powell achieves the desired pursuit tracking results in the most direct way.

As a means of evaluating the simulated performance of the human operator when performing this task, the performance data of the attacking aircraft was subjected to a number of spectral analysis operations. These spectral operations compared the frequency content of the data obtained from the simulation to actual data obtained from combat flight maneuvers. For both sets of data the evaders performed the same identical tactics.
The results of the study have lead to the selection of upper and lower limits to be used for the variable parameters which are optimized in the human model. The established constraints which correspond to observed pilot reactions in simulator studies are used to implement the adaptive linear model of the human pilot to achieve precision tracking for long periods of time for a variety of evasive maneuvers.
SECTION I

INTRODUCTION

Automatic and manual control technology has progressed to the point that any control system can be simulated as long as the human factor is ignored. However, the human operator is a vital part of many control systems. Contrary to some current public opinion, the human is not obsolete as an integral part of present and future control systems. The fact that a human operator is an inexpensive means of performing many functions which require a logical decision continues to be justification for his existence.

Because of the need for utilizing the human operator in control systems, his ability has received much attention in the past few years. Unfortunately, even with the large amount of effort in this area, no definitive model for the human operator exists at present. This is not to imply that models of the human operator do not exist; but rather that a countless number of indefinite models exist each describing the human operator for a particular condition. The models differ due to the fact that each evolved from observing the human in totally different circumstances. Furthermore, each model seemingly tried to take into account the points that previous models had failed to consider.
Due to the evolution of high speed aircraft, the need for a human operator to make rapid decisions has been further increased. Unbelievable as it may sound, some aircraft companies, because of this human factor, still design and build a vehicle before they are able to evaluate the actual performance characteristics. This faulty reasoning is simple. Automatic flight control systems technology (autopilot design) presently makes use of either fixed or scheduled control techniques. Both techniques fail in their attempt to provide suitable aircraft response throughout the full range of flight dynamics because of the need to compile and store an enormous amount of dynamics data on the various states of the aircraft. This present state-of-the-art in aircraft control needs a human model which can monitor its own performance by evaluating the effectiveness of the aircraft response and then modifying its own parameters automatically in order to achieve the desired aircraft performance. This technique is commonly referred to as self-adaptive control (Figure 1). This type of control model continually evaluates the performance of the aircraft and then "adapts" itself based on a logical adjustment of the parameters in the autopilot system.

OBJECT OF THE STUDY

The objective of this study is the simulation and evaluation of the tracking ability of the human operator in the role of a pilot of a high speed aircraft which is subjected to various random evader tactics. Specifically, this study is intended to contribute
Figure 1  Self Adaptive Control Model
to the determination of the variable parameters of the human操
operator model through the use of an optimization scheme which automatically selects the optimum model parameters over small increments of the flight regime.

It is intended that this study be unique because of the fact that actual attacker-evader flight regimes were used as a means of evaluating the model of the human operator. This type of study as opposed to a study using theoretical data or simulator data places the operator model in an environment in which personal danger is a factor. This factor is exemplified by the evasive action that was observed in the experimental flight regimes.

SCOPE OF THE INVESTIGATION

A realistic model had to be selected in order to develop a system which would rapidly and automatically determine the variable parameters in the model of the human operator. There is little significance in optimizing parameters of a model which does not depict the physical system. To select the appropriate model a literature search was conducted. On the basis of the literature study on previous investigations utilizing a human model, a continuous linear mathematical model for the human operator was selected.

Using this model and a maximum target kill performance criteria, an optimization scheme was developed which would maximize the target kill probability. The scheme for optimization used is a modification of the method accredited to M. J. D. Powell. This method was
selected because of its ability to obtain adaptive capabilities without requiring a direct measurement of a significant system parameter.

The method of model evaluation was based on the implementation of the human model into an existing digital computer simulation used for aerial combat engagements. It should be noted that a significant part of the overall study was directed towards the development of the aerial simulation; however, the simulation should be considered only a tool for the analysis.

The major asset of the aerial simulation is the predefined evader option. This particular option enabled the implementation of the actual combat aerial engagements for controlling evader manuevers. This means that the human model could be subjected to actual random evader tactics and data could be collected which would compare the performance of the human model to the actual performance of a trained combat pilot.

The data which was assembled was analysed in two distinct manners. First the data was analysed from an effectiveness viewpoint. Total tracking error, system response, total gun firing time and, hits obtained were among the subjects of interest in this phase of the analysis. The second method of evaluating the model through the use of this performance data was a series of spectral analysis operations. The use of statistical theory in this part of the analysis enabled the frequency content and coherance of the aerial flight data to be compared in an effort to
verify when an appropriate equivalent model for the human pilot had been found.

SUMMARIZATION

In summary the scope of this work was the simulation and evaluation of a human pilot when subjected to random evader tactics. This was accomplished through the implementation of a linear continuous model with adaptive capabilities. This model was incorporated into a digital aerial simulation and evaluated with respect to actual aerial data from both a spectral and an effectiveness viewpoint.
SECTION II
DETERMINATION OF CONCEPTS

TASK DETERMINATION

As did most present day control theory, human operator systems as such had their birth during World War II. During the following years, human operator technology did progress; however, the advances were not uniform. Both basic categories of human operator systems which developed as this man-machine problem became more clearly defined progressed at different rates as the technical area broadened.

Considerable attention was given throughout this period toward the compensatory systems (Figure 2). Compensatory is the name used by engineering psychologists; however, control engineers will recognize this system as a simple single loop feedback system. This type of system is normally depicted as a series of displays, usually visual in nature, having two indicators, one stationary and one movable. In this system the stationary point is characterized as the target and the movable point is characterized as the controlled element. When the
Figure 2 Compensatory Tracking System
operator has manipulated the controlled element in such a manner so as to superimpose the two indicators, the vehicle is on target. The difference that is observed when the indicators are not superimposed is called the error. The error is sensed by the human as the difference between the reference input to the system and the system output. The fact that the error cannot be detected at its source is the distinguishing feature of compensatory systems. The operator has no way of knowing if the target has changed course or if the tracking is inaccurate.

The second category of human operator systems, the pursuit system illustrated in Figure 3, treats this problem in a different manner; but, unfortunately this somewhat more difficult system has received very little attention. For the pursuit system, both the locations of the target and the controlled element are known to the operator and their relationship to each other can be visualized. This gives the operator the opportunity to observe the path the target has taken. It further leads the operator to make logical decisions concerning the future course of the target. It should be noted however, that the operator in reality cannot know for sure the future course of the target.

MODEL DETERMINATION

During the post war period, two predominant mathematical models for the human operator evolved, the quasi-linear model and the continuous model. The evolution of these models originated
Figure 3 Pursuit Tracking System
when the first model for the human operator was developed in 1947. This model proposed by Tustin was a simple linear model. In most respects, it was identical to the simple deterministic linear control systems of the time; however, Tustin was the first to realize that the human operator has behavior patterns which are in general non-linear. To adjust for the non-linearity Tustin added to the linear model a term to account for the residue or that part not attributed to portion of the system representable by the linear model. This adjustment factor was labeled the remnant. From this point his method was simply to select the form of the linear model which would minimize this remnant. This is still the basic idea behind the quasi-linear models in use today.

Advocates of the quasi-linear model of the human operator treat the model as an equivalent system which exhibits input and output relationships analogous to the behavior patterns of human beings, regardless of the non-linearities which do exist. They maintain that the human operator behavior is generally non-linear; but, within certain ranges of input, the responses are linear enough in nature to be treated as linear functions.

The quasi-linear model has evolved to the point that today it is an analytical-verbal describing function in nature. The analytical part of the model has the form of a generalized describing function; and, the verbal part of the model is a series
of "adjustment rules" which indicate how the parameters in the
generalized describing function should be adjusted to yield
approximate human behavior for any situation which may be of
interest.

A considerable amount of effort with the quasi-linear model
has been performed by D. T. McRuer and E. S. Krendel. The most
generalized analytical describing function which applies for one
and two dimensional control tasks was developed by McRuer and
Krendel and has the following form:

\[ Q_p = K_p e^{-j\omega \tau} \frac{\left( T_L j\omega + 1 \right) \left( T_I j\omega + 1 \right)}{K_T \frac{a_T}{\alpha_T}} \]

Where:

- \( K_p \) = Human Operator Gain
- \( \tau \) = Reaction Time Delay
- \( \frac{T_L j+1}{T_I j+1} \) = Equalization Characteristics
- \( K_T \frac{a_T}{\alpha_T} \) = Indifference Threshold Describing Function
- \( \frac{j\omega}{\omega_N}^2 + \frac{2\varepsilon_N j}{\omega_N} + 1 \) = Neuromuscular System Characteristics

It should be noted that McRuer and Krendel have described
this portion of the analytical-verbal describing function in
terms of the frequency operator. This is done to emphasize that
this model of the human operator is only valid in the frequency
domain and only exists when conditions are essentially stationary.
In this case stationary conditions imply that the input to the
model be independent of time (random) and that the element that
the human is controlling also be time invariant. Quite obviously,
this is a major disadvantage of using a quasi-linear model.

It should also be noted that when high frequency excitations
are ignored, the model reduces to a much simplified form.

\[ 0_p = \frac{K_p e^{-j\omega T}}{(T_L j + 1)(T_N j + 1)} \] (II-2)

This reduced expression is identical to the continuous linear
model form and will be discussed in detail in a latter portion
of the investigation.

In conjunction with the analytical part of the model a series
of verbal adjustment rules have evolved in order to minimize the
remnant. These rules are rather loosely defined; but, generally
follow accepted ideas about the way a human should respond. The
most basic rule of the verbal part of the model is stability.
The operator always adapts the form of the equalizing characteristics
to achieve stable control regardless of the task. The operator
also adapts in order to achieve favorable low frequency closed-loop
system response. In other words the operator adapts a lead when
there is a phase lag in the dynamics of the system which he is
controlling. The amount of lead depends upon the size of the system phase lag. Furthermore, a larger lead is generated when the dynamics of the system and the reaction dead time of the operator are such that a lead would be necessary in order to improve the system response. Finally, it is thought that the operator then adjusts the describing function parameters further to achieve an optimum closed-loop frequency performance with respect to some performance criteria. The general feelings on this performance criteria indicates that the human operator uses something similar to the minimum mean squared tracking error.

The verbal part of the describing function model of the human operator is subject to much criticism. The greatest part of this criticism is centered on the uncertainty of these adjustments as well as the uncertainty of the performance criteria.

The other mathematical model which has evolved as a result of the effort expended in the area of man-machine systems is a linear continuous model. This model offers a number of advantages over the quasi-linear describing function verbal model. The most significant advantage is that the continuous model is also valid when it is not used in the frequency domain. This feature allows the human operator to be represented as a transfer function. Since most other system components can be represented as transfer functions, it is only natural to also think in terms of a human transfer function.

A transfer function is merely a mathematical description of the ratio of the output to the input of a control element. For
a human operator this ratio relates the sensory input (usually visual signals) and the physical response (the operation of some control device). The human transfer function can be considered as possessing the various human features such as sensation, perception, reaction time delay, decision logic, and the means of implementing physical control.

This present study incorporates the continuous model for the human pilot. This decision was influenced by the independent work done in this period primarily by Adams (2), Knoop (3), Fu (3), McRuer (5), Kendel (5), Soliday (7), Schohan (7), Kuehnel (8), Potto (9), Costello (10), and Pew (11). All these authors and many more believed and/or demonstrated that for their particular investigations the human operator could be accurately represented by a linear transfer function. Furthermore, most current technical articles on aircraft control display linear transfer function models. Obviously not all these authors used the same model; however, the general indications have led to a model of the form similar to the previously noted quasi-linear model:

\[
\frac{Ke^{-\tau_D S}}{(\tau_N S + 1)(\tau_I S + 1)} \prod_{k \leq 1} \left( 1 + \frac{1}{\tau_k S} \right)
\]

where

- **K** is Pilot Gain,
- **\(\tau_D\)** is Pilot Dead Time,
- **\(\tau_L\)** is Lead Time Constant,
- **\(\tau_N\)** is Neuromuscular lag, and
- **\(\tau_I\)** is Lag Time Constant.
For this human pilot transfer function the pilot gain term \( K \) is the predominant human control characteristic. Since the gain term is the main factor in the output signal to input signal ratio, it is responsible for converting the stimulus signal into a suitable scaled command to be sensed by the neuromuscular system. The most important factors which influence the pilot gain term are the aircraft transfer function and the performance limited tracking task. The nominal range for the pilot gain as indicated from the literature is 0.1 to 100.0.

The reaction dead time is the unavoidable delay which is observed between the detection of a signal and the initial response to this signal. Sensor excitation (the retina in the visual case), nerve conduction, computational lags, and other data processing activities in the central nervous system account for the delay time. This reaction dead time is strongly dependent on the type of signal the human receives, and is a direct function of the amount of information which must be extracted from the signal. If the signal that is received is somewhat predictable, the reaction time is on the order of one tenth of a second; whereas, for unpredictable signals, the reaction time is generally on the order of one-half of a second. Pilot reaction dead time is considered to be constant as evidenced by investigations which have revealed it to be essentially invariant with respect to input excitation and airframe dynamics when a random appearing task is observed.
The pilot dead time coupled with the neuromuscular term,
\((e^{-t_D/\tau_D}+1)\) represent the physiology of the human pilot. The
neuromuscular time constant can be partially adjusted for each
task but because the range of values is so small and the actual
nature of the adjustment is so obscure, this parameter variation
is normally ignored in applications. The nominal value usually
selected to represent the neuromuscular time constant is 0.1
second.

The anticipatory action of the human is exemplified in the
human transfer function as the pilot lead term, \((\tau_L+1)\). The
pilot lead time constant is the second most critical parameter
in the mathematical model of the human pilot. It must modify
the stimulus signal into a suitably phased neuromuscular command
to maintain overall system operation. The lead time constant is
generally found in the range of one tenth of a second to two and
one half seconds.

The remaining term in the human transfer function is the
pilot lag term, \((\tau_I+1)\). Equalization or compensation for the
changing characteristics of the aircraft and the pilot reaction
time delay is represented by the pilot lag time constant.

Opponents of the human transfer function maintain that no
one transfer function can be utilized for each and every man-
machine arrangement; but, they are the first to admit that for a
given operation, when an appropriate transfer function has been
found, it is possible to utilize this transfer function in the design of a physical system to perform in a reasonably optimum manner. An optimizing technique is then needed and essential to the designer. Thus a suitable transfer function could be obtained and the parameters of this function adjusted automatically during the actual tracking phase that would suffice for a reliable and effective simulation. This would also predict new dynamic characteristics for the human with each new enviromental change to which he is subjected.

PERFORMANCE CRITERIA

To implement this human transfer function with adaptable human behavior, certain optimum design principles had to be employed. These principles dictate that systems of this type should modify their parameters in a manner which would minimize an error function; that is, these systems should provide a means for adjusting the variable parameters of the human model in order to achieve the minimum of some performance criteria in the most direct way. Since optimum performance has as its basis the performance criteria employed, the optimum can be no better than the particular performance criteria selected.

Performance criterion, index of performance, performance measure, figure of merit, and performance specification are all equivalent terms found in the present literature to include in one number, a measure for the performance of the system. This
number is the major factor in adaptive controller design. The performance criterion can be defined in an ideal manner, but eventually, the design must make use of what data is available and the physical system constraints, and these are seldom ideal.

Some of the standard performance criteria such as:

**MEAN SQUARE ERROR**

\[ E_{ms} = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} e^2(t) \, dt \] (II-4)

**INTEGRAL SQUARED ERROR**

\[ ISE = \int_{0}^{\infty} e^2(t) \, dt \] (II-5)

**INTEGRAL OF TIME AND SQUARED TIME MULTIPLIED BY SQUARE ERROR**

\[ ITSE = \int_{0}^{\infty} te^2(t) \, dt \] (II-6)

\[ ISTSE = \int_{0}^{\infty} t^2 e^2(t) \, dt \] (II-7)

**INTEGRAL OF THE ABSOLUTE VALUE OF THE ERROR, AND THE TIME WEIGHTED ABSOLUTE ERROR**

\[ IAE = \int_{0}^{\infty} |e(t)| \, dt \] (II-8)

\[ ITAE = \int_{0}^{\infty} t|e(t)| \, dt \] (II-9)

are available for static optimization; but, have little meaning when used in conjunction with an adaptive control system. It has been found that most adaptive systems make use of a criterion
unique to the particular problem. When the problem of tracking is considered, the maximum target kill probability under all conditions must be the ultimate performance criterion.

In order to achieve maximum target kill probability, the performance criterion must reflect the probability of miss. This miss probability is a function of the range between the two aircraft and the total angle off. The need for including range as part of the performance criteria is illustrated in Figure 4. No matter what type of ballistic properties a gunnery system incorporates, the same general shape is evident in the range versus probability of kill curve. Because of the almost exponential decline, it can be concluded that a constraint must be placed on the range between the two aircraft in order to increase kill probability. The most effective way of including this constraint is by determining an optimum range for the particular gunnery system considered and penalizing for deviations away from this optimum.

The other, and perhaps the most important factor, which must be included as part of the performance criterion is the total angle off between the two aircraft, (Figure 5). This angle is composed of the vector sum of the elevation and traverse angles as well as the lead angle between the two aircraft. The importance of the total angle off is expressed when precise tracking is required. In order for the performance criterion to maximize the target kill probability, it initially affects closing on the target,
Figure 4  Range Error Criteria
Figure 5  Tracking Error Geometry
and after this is achieved, the angle off, (the total tracking error), is minimized. For either part of the criterion to have emphasis when needed, a normalization is required. This normalization is required because variables which have different physical dimensions will have different ranges of variation and different impact on the performance criterion. This performance criterion with these characteristics, is easily implemented and does take into account the factors which contribute to maximize target kill probability.
SECTION III

METHOD OF MODEL VARIATION

TECHNIQUE SELECTION BASED ON PREVIOUS STUDIES

Despite the many applications of operator models, the literature reveals that models have not been extensively employed as a functional part of an adaptive system. The system developed by Knoop (3) and Fu (3) was one of the exceptions. In their study a true adaptive model was used; but, the adaptive method was utilized only in one parameter and the control element was merely a pure mass. Other authors who claim to have adaptive type systems use the reference technique (Figure 6). This technique employs a reference model which influences the parameter control signal.

Most current adaptive strategies have been based upon performance surface-slope measurements. The most common of these are the steepest descent and the conjugate gradient methods. These gradient techniques use as a means of minimization a search direction which is perpendicular to the most recently determined contour tangent. This gradient direction will yield the greatest rate of change of the performance function; however, the determination of these search directions requires a large number of function
Figure 6 Reference Model Adaptive System
evaluations. In addition, gradient techniques require the calculation of derivatives.

Unfortunately in most cases, the calculation of first derivatives is laborious and practically impossible. These circumstances necessitate a minimization procedure which would calculate the minimum of a function of several variables without calculating derivatives. In this case the basic method introduced in 1964 by M. J. D. Powell (13) is regarded as the most practical approach. This decision was based primarily on the published works of R. Fletcher (14) and M. J. Box (15). Both investigators conducted research toward evaluating the efficiency of the different optimization techniques in terms of the number of iterations and accuracy of convergence. Fletcher's paper which appeared in 1965 considered the efficiency of methods which minimize functions without evaluating derivatives. Fletcher concluded that the most efficient methods involved successive linear minimizations along conjugate gradients which were generated as the minimization proceeded. Because of this conclusion, Fletcher reviewed three of the most prominent methods. The first considered was a method developed by W. H. Swann in 1964, the second was by C. S. Smith in 1962, and the final method considered was M. J. D. Powell's method.

Fletcher incorporated four test functions in order to develop conclusions. The functions tested were

1. A parabolic valley (Rosenbrock, 1960),
2. A helical valley (Fletcher and Powell, 1963),
3. A function of four variables (Powell, 1962), and
4. A Chebyquad function with 2, 4, 6, and 8 variables.

Fletcher compared these three optimization procedures for all the above functions and listed; the difference between the function and its value at the minimum, the cumulative number of function evaluations and the number of linear minimizations which were required. These comparisons are shown in Table I. From this study Fletcher concluded that Powell's method was the best.

The paper published in 1966 by M. J. Box considered the optimization problem in which the performance function was highly non-linear and contained twenty independent variables. Box compared eight methods. The first four methods were direct methods which did not require the calculation of derivatives. Those included were; the method of Swann, 1964; Rosenbrock's method 1960; the Simplex Method, 1965; and the method of Powell, 1964. The next two methods considered were gradient methods which required the calculation of derivatives. They were Fletcher and Powell's Davidon Method and the conjugate direction method of Fletcher and Reeves. Box also considered Powell's method for minimizing a sum of squares and Barnes method of solving sets of simultaneous non-linear equations. Box published his results through the use of equivalent function evaluations. Each entry by a gradient method to its subroutine was regarded as \((n + 1)\) function evaluations when compared to the direct search methods.
TABLE I

FLETCHER COMPARISONS

<table>
<thead>
<tr>
<th>Case</th>
<th>Iterations</th>
<th>Function</th>
<th>No. of Functions</th>
<th>No. of Minimums</th>
</tr>
</thead>
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<tr>
<td>Parabolic</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Valley</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Swann</td>
<td>21</td>
<td>$1.5 \times 10^{-12}$</td>
<td>187</td>
<td>46</td>
</tr>
<tr>
<td>Powell</td>
<td>14</td>
<td>$1.3 \times 10^{-16}$</td>
<td>158</td>
<td>39</td>
</tr>
<tr>
<td>Smith</td>
<td>19</td>
<td>$3.6 \times 10^{-16}$</td>
<td>234</td>
<td>58</td>
</tr>
<tr>
<td>Helical</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Valley</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Swann</td>
<td>21</td>
<td>$2.1 \times 10^{-14}$</td>
<td>266</td>
<td>69</td>
</tr>
<tr>
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<td>180</td>
<td>56</td>
</tr>
<tr>
<td>Smith</td>
<td>14</td>
<td>$1.5 \times 10^{-12}$</td>
<td>365</td>
<td>101</td>
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<td>Powell's Fcn.</td>
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<td></td>
</tr>
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<td>Swann</td>
<td>16</td>
<td>$2.1 \times 10^{-14}$</td>
<td>253</td>
<td>69</td>
</tr>
<tr>
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<td>$5.3 \times 10^{-9}$</td>
<td>235</td>
<td>79</td>
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<tr>
<td>Smith</td>
<td>12</td>
<td>$3.7 \times 10^{-11}$</td>
<td>533</td>
<td>145</td>
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<tr>
<td>Chebyquad-2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Swann</td>
<td>7</td>
<td>$1.6 \times 10^{-19}$</td>
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<td>$8.6 \times 10^{-14}$</td>
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<td>13</td>
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<tr>
<td>Smith</td>
<td>4</td>
<td>$1.5 \times 10^{-13}$</td>
<td>51</td>
<td>13</td>
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<td></td>
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<td>Swann</td>
<td>10</td>
<td>$2.2 \times 10^{-14}$</td>
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<td>45</td>
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<tr>
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<td>$4.1 \times 10^{-14}$</td>
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<td>32</td>
</tr>
<tr>
<td>Smith</td>
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<td>49</td>
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<td></td>
<td></td>
<td></td>
</tr>
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<td>24</td>
<td>$3.9 \times 10^{-12}$</td>
<td>532</td>
<td>149</td>
</tr>
<tr>
<td>Powell</td>
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<td>$6.8 \times 10^{-14}$</td>
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<tr>
<td>Smith</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Swann</td>
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<td>$1. \times 10^{-10}$</td>
<td>739</td>
<td>189</td>
</tr>
<tr>
<td>Powell</td>
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<td>$5.7 \times 10^{-13}$</td>
<td>537</td>
<td>200</td>
</tr>
<tr>
<td>Smith</td>
<td>10</td>
<td>$3.2 \times 10^{-8}$</td>
<td>1652</td>
<td>421</td>
</tr>
</tbody>
</table>
Box concluded that the Davidon method modified by Fletcher and Powell was the most consistent. However, Powell's (1964) method performed equally as well as Davidon's method for five, ten, and twenty dimensional test functions. Therefore, Box concluded that Powell's method was virtually as efficient as Davidon's method and more effective than the other non-gradient methods. A summary of his findings are presented in Table II.

Because of the overall performance of the system as well as the ease in which the method of Powell could be applied. The non-derivative method of M. J. D. Powell was selected to perform the human model variations. Using this method to adjust the variable parameters of the human model in order to achieve the desired pursuit tracking is considered to be the most direct way to represent realistic human behavior in every flight regime.

**TECHNIQUE DESCRIPTION**

Powell's method is essentially a contour tangent elimination method. This class of optimization methods use the locally measured tangent to the performance contour as a boundary elimination. Each tangent generated by this type of procedure decreases the area of the search quite rapidly since the information from all past explorations is incorporated into each new tangent. Obviously, the contour tangent elimination methods have as their major advantage the fact that the direction of the search vector and the method of function minimization does not depend upon the calculation of derivatives. In addition, contour tangent elimination has the
### TABLE II

**BOX COMPARISONS**

**Function Evaluations**

<table>
<thead>
<tr>
<th></th>
<th>2 Dim.</th>
<th>3 Dim.</th>
<th>5 Dim.</th>
<th>10 Dim.</th>
<th>20 Dim.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swann</td>
<td>78</td>
<td>448</td>
<td>303</td>
<td>2269</td>
<td>5183</td>
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<tr>
<td>Rosenbrock</td>
<td>96</td>
<td>347</td>
<td>465</td>
<td>1210</td>
<td>10208</td>
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<td>Simplex</td>
<td>41</td>
<td>119</td>
<td>229</td>
<td>752</td>
<td>6970</td>
</tr>
<tr>
<td>Powell</td>
<td>64</td>
<td>78</td>
<td>104</td>
<td>329</td>
<td>1519</td>
</tr>
<tr>
<td>Conjugate Gradient</td>
<td>93</td>
<td>564</td>
<td>354</td>
<td>1639</td>
<td>4200</td>
</tr>
<tr>
<td>Davidon</td>
<td>51</td>
<td>92</td>
<td>114</td>
<td>396</td>
<td>1764</td>
</tr>
</tbody>
</table>
ability to determine an optimum in a relatively small number of function evaluations.

In order to create an understanding of Powell's method for optimization as well as to present a general introduction of optimization, the most basic gradient procedure, Steepest Descent is illustrated. First a function of several variables which is to be minimized is defined as

\[ f = f(x_1, x_2, x_3 \ldots, x_n) \]  

(III-1)

In its most general form the steepest descent procedure can be defined in the following manner:

\[ \sigma_i = \left| \frac{\partial f}{\partial x_i} \right| \left\{ \sum_{i=1}^{n} \left( \frac{\partial f}{\partial x_i} \right)^2 \right\}^{1/2} \]  

(III-2)

where \( \sigma_i \) represents the components of a unit vector defining the required directions for the search. For two parameters the process is illustrated in Figure 7. The value of the function \( f \), is calculated along the direction \( \sigma_0 \) until a minimum value is obtained. This is geometrically illustrated as the point which is tangent to the performance curve with the lowest value. Now using this new point as a base for the newly calculated direction, the process is repeated until the minimum is found. It should be noted that for two variables the method of steepest descent is accomplished by changing one parameter at a time, and the directions used are a function of the starting point. It should also be noted by this
Figure 7  Steepest Descent Procedure for Two Dimensions
simple example that the problems which must be handled by an mini-
mization procedure are,

1. Determination of the direction of the step, and
2. Determination of the proper step length.

It should also be apparent at this point that the accuracy of the optimization method is severely affected by the determination of the proper scale factor to insure a correct length.

The steepest descent method, as well as most other methods, starts from an initial point in N-dimensional space. From this point a search vector of the form \( x_1 = x_0 + \lambda A x \) is computed. This search vector has as its primary goal the position of a new and better point, or the point along the vector where the performance function is a minimum. The location of this point along the vector is mathematically determined by the scale factor \( \lambda \) which is the distance from the starting point to the relative minimum position. This is illustrated in Figure 8. Therefore, the method used for minimization must be able to determine a sufficiently small scale factor, such that the function \( f(x_0 + \lambda A x) \) will have a smaller value than the function \( f(x_0) \). This indicates that the increment in the search vector must point in a direction which decreases the performance function.

In the actual stepping procedure to determine a relative minimum point, the following technique is employed. For the initial position, a value for the function is determined. A step of length \( \text{h} \) is then taken and the value of the function is
Figure 8 Minimization Stepping Procedure
again calculated. At this point a decision is made concerning the direction of the stepping procedure. If this new value is less than the initial calculation the process of finding a relative minimum is proceeding in the correct direction. However, if the new value is greater than the initial calculation then the direction of the step is incorrect. To alleviate this error, the roles of the two calculations are then interchanged and the process proceeds again in the correct direction. Once the correct direction is insured, the step length, h, is doubled and another calculation of the value of the function is made and checked in order to determine if a minimum has been achieved. This is then repeated until a minimum is found. The success of the optimization procedure depends on the search vector; but, the accuracy of the solution depends upon the proper step length.

Using the concepts of direction and step length for the search vectors established, the non-gradient method of Powell will be considered in detail. Powell in his original paper lists four steps to implement his procedure.

Using the best known approximation to the minimum, p_0, a search in N-linearly independent directions \( \xi_1, \xi_2, \ldots, \xi_n \) is conducted for the N-dimensional problem. Initially these directions can be selected to be the coordinate directions. For each of these N searches a value for the step length, \( \lambda \), is calculated such that \( f(p_{n-1} + \lambda \xi_n) \) is a minimum. After the N searches are performed the independent directions for the search are again evaluated by
replacing \( \xi_n \) by \( \xi_{n+1} \) for \( n = 1, 2, \ldots, n-1 \) and \( \xi_n \) by \( (p_n - p_0) \)
when \( n \) is equal to the number of searches. Geometrically this newly created direction is the line joining the initial approximation for the minimum and the approximation for the minimum obtained after the \( N \) linearly independent searches. A search is then made along this direction until a step size is determined which will minimize \( f[p_n + \lambda(p_n - p_0)] \). This new point replaces \( p_0 \) as the best approximation of the minimum and the procedure is iterated until an absolute minimum is determined.

Powell's procedure can be illustrated by a simple example. Consider the two dimensional case of determining the optimum value of the function:

\[
f = 20(X_1 - X_2 - 10)^2 + (X_1 - X_2)^2 \tag{III-3}
\]

The trivial solution \( X_0, (0,0) \) which is a good starting approximation to the minimum, yields \( 2000.0 \) as a value of the function.

Powell's method first performs two searches along linearly independent directions. Using the coordinate directions \( \xi_1 = (1,0) \) and \( \xi_2 = (0,1) \), the first search is then to minimize the function:

\[
f = 20(X_1 - 10)^2 + (X_1)^2 \tag{III-4}
\]

This first search is illustrated in Figure 9 as the search along line ABC. The distance from point A to point B which is \( \lambda \), represents the step size in the \( \sigma_1 \) direction to \( B, (9.5, 0.) \) which minimizes (III-3) to a value of approximately 110. The second search in the direction \( \sigma_2 \), BDF, seeks to find the point D which minimizes the function:
Figure 9 Non-Gradient Optimization Procedure for Two Dimensions
\[ f = 20(9.5 - X_2 - 10)^2 + (9.5 - X_2)^2 \quad (III-5) \]

This point D is calculated to be (9.5, .928) and the value of the function is reduced to approximately seventy-seven. Since this is only a two dimensional search, the next search is made along the line AGD to find a new value of \( \lambda \) to minimize the function

\[ f[p_n + \lambda(p_n - p_o)] \]

or

\[ f[p_D + (p_D - p_A)]. \]

The equation of the line AGD is

\[ X_2 = .098 X_1 \quad (III-6) \]

and the function to be minimized becomes:

\[ f = 20(1.098 X_1 - 5.)^2 + (.902 X_1)^2 \quad (III-7) \]

The solution of this equation yields the point G, (5.26, .515), with a function value of approximately thirty-eight.

The point G then replaces the initial starting value as the best approximation of the minimum and the same procedure is again followed until the procedure converges on an absolute minimum. The ability of Powell's method to rapidly converge on a minimum is explicitly shown in this example. In only one search down the N-lineary independent directions, the value of the variables in the function were determined which reduced the function from two thousand to thirty-eight.
SECTION IV

METHODS FOR ANALYSIS

DIGITAL ANALYSIS

In order to evaluate the tracking ability of the human pilot subjected to various random evader tactics, a digital computer simulation was used as the primary tool for the analysis. This simulation had as its base the program supplied to the Department of Defense under USAF Contract number FO 8635-68-C-0008. This program, which originated at the McDonnell Aircraft Company, was entitled IMAGE (Improved Model for Aerial Gunnery Effectiveness). The original purpose for the development of this program was to simulate and control aircraft performance, along with the evaluation of gunnery effectiveness in air-to-air combat situations. However, because of its inability to model the human pilot for a variety of flight regimes, the simulation lacked the necessary flexibility a program of this type should provide in order to be a useful tool for total system evaluation. For this reason the human pilot analysis complements the IMAGE simulation.

The program IMAGE is illustrated in Figure 10 and consists of modular units with three major quasi-independent simulations. The
Figure 10  IMAGE Simulations
three simulations are:

1. Flight Path Generation
2. Fire Control
3. Terminal Effectiveness.

The majority of the programming effort in the flight path simulation is concerned with the pilot control logic which enables the attacking aircraft to move into a position which is suitable for firing to commence. This control logic is not an effort to simulate a human operating the aircraft; but rather, a substitution for the pilot's thought process with specific maneuvers consistent with tactical objectives. The logic incorporated in the flight path simulation is for the attacker to always fly a pursuit course in order to convert to a gun firing position.

The logic used in the flight path generation for the evader can be implemented in either of two ways. The first method of implementing the evasion logic is by simply using the maneuver parameters as specified by the relative geometry boundaries. The parameters are part of the input data to the IMAGE program and can be selected in such a manner as to simulate any desired evader tactic.

The second method of selecting evasion logic is through the use of a preprogrammed target trajectory. This canned target feature enables the implementation of actual combat aerial engagements for controlling the evader maneuver. By making use of the canned target feature, data obtained from actual
flight regimes was implemented in the flight path generation and a useful tool for analysis developed. The knowledge of both attacker and evader position and velocity for every moment of an engagement allowed a comparison to be made between the human pilot transfer function and the real aircraft pilot.

In addition to the digital analysis made from the comparison viewpoint, the terminal effectiveness simulation analyzed the gun characteristics for the attacker. Since the terminal effectiveness portion performs a projectile trace, it is capable of determining the minimum miss distance between each projectile and the evading aircraft. From this information the terminal effectiveness portion is capable of determining the probability of hitting the target aircraft and the probability of target kill. All of these calculations reflect the performance ability of the human transfer function.

Although the flight path generation offered a means of implementing the known behavior of an evader, and the terminal effectiveness provided a quick means of evaluating the flight, the fire control simulation was the most critical portion of IMAGE for the digital analysis. Figure 11 shows more clearly the interaction between the flight path and terminal effectiveness when utilized by the fire control portion of the simulation.

The fire control simulation has as its main purpose the aiming of the attacker's guns at the evading target. To accomplish this task efficiently, the problem of precision tracking is introduced.
Figure 11 Interactions Between Flight Path, Terminal Effectiveness, and Fire Control
In order to illustrate how the human transfer function is coupled to the tracking problem a further investigation of the overall make up of the fire control simulation is in order.

In its most basic form, the fire control simulation is illustrated in Figure 12. This simulation takes over when the flight path generation maneuvers the attacking aircraft into a position for possible firing. It expands the three-degree-of-freedom equations found in the flight path portion into a full six-degree-of-freedom system with all necessary aerodynamic data as well as a sight mechanism. It then provides a means of steering the attacking aircraft into a suitable firing position. Converting to the suitable firing position is the purpose of the human transfer function when it minimizes the performance criterion. The integration loop which accomplishes the above task is shown in Figure 12. As can be observed, the integration loop for the fire control simulation is composed of five main subroutines:

1. AIRFII (Airframe)
2. RGDCII (Geometry)
3. ALCSII (Lead Computing Sight)
4. AUTSII (Augmentation)

The airframe subroutine (AIRFII) contains the equations of motion for the aircraft structure. It computes the normal and lateral accelerations on the aircraft and yields such variables as velocity, angle of attack, sideslip angle, the pitch, roll and yaw body rates, and the Euler angular orientation of the aircraft.
Figure 12 Major Portions of the Fire Control Integration Loop
From this subroutine the roll attitude and the normal acceleration of the aircraft are supplied to the pilot subroutine in order to minimize the tracking error.

Subroutine RGDCII maintains all the necessary geometrical calculations for the aircraft flight. This subroutine is responsible for computing the geometrical parameters of the trajectory of the attacking aircraft, the angular orientation of the line of sight from the attacking aircraft to the evading aircraft, and the angular error rates experienced by the attacking aircraft. The geometry subroutine supplies the elevation and traverse errors between the line of sight and the gunline to the pilot subroutine as well as to the performance criterion subroutine.

The lead computing optical sight subroutine, (ALCSI2), is responsible for calculating the disturbed reticle lead angle with respect to the aircraft gunline. This is the angular component between the gunline of the attacking aircraft and the line of sight to the target aircraft. The lead angle components which are computed as well as their rates are transmitted to the pilot subroutine in terms of the elevation and traverse directions.

The signals from the pilot subroutine are acted on by the argumentation subroutine (AUTSII), to adjust the control surface deflections. This subroutine links mechanically the deflections of the stabilator, aileron, and rudder to the pilots commands. It also has provisions for linking the pilots commands to the control surfaces by purely electrical means or a combination of mechanical and electrical devices.
The final and most important subroutine in the fire control integration loop is the pilot subroutine, (PILTI1). As noted above, its main duty is the generation of the signals in the elevation, bank, and heading channels which control the deflections of the stabilator, aileron, and rudder. The pilot subroutine calculates the elevation and traverse tracking errors and then uses these tracking errors in implementing the human transfer function in order to minimize the total tracking error between the disturbed reticle lead angle and the gunline of the attacking aircraft. Both the elevation and traverse portions of the pilot subroutine are composed of conversion factors and compensation networks which tend to remain constant for a given aircraft configuration; but, both portions also contain the transfer function model for the human operator which is dependent on flight conditions. These human transfer functions which are represented as the autopilot in each channel are shown (with the appropriate system interactions) in Figure 13 and Figure 14.

Roll, yaw, and pitch are the three coupled axis systems which the individual mathematical model for the pilot incorporated. In each channel a model of the form:

\[
\frac{-T_D}{K_e(T_L + 1)} \frac{(T_I + 1)}{(T_I + 1)(T_N + 1)}
\]

is utilized to sense the appropriate tracking error and generate a suitable signal in order to control the attitude of the aircraft.
Figure 13 Autopilot Interaction in the Elevation Channel
Figure 14 Autopilot Interaction in the Traverse Channel
This model simulates for each individual channel (roll, pitch, yaw) the pilot's awareness of the performance of his aircraft and his reactions to different flight maneuvers.

For example, consider the reactions of the pilot transfer function in the elevation channel. In this channel the human pilot is modeled as a second order transfer function plus dead time and is allowed to sense the amount of error which exists between the present line of sight of the gun system attached to his aircraft, and the necessary position of his aircraft to enable a line of sight which will insure his guns to be firing with a large probability of kill. After experiencing a period of reaction dead time in accordance with the reaction time constant, the pilot model then is capable of automatically adjusting its most critical parameters that of gain and lead time. For this particular channel the anticipatory action of the pilot is reflected by the lead time parameter ($T_L$). The combination of gain and lead time along with neuromuscular lag and pure lag produces a normal acceleration command to the stabilator control system. Limit provisions are also included in accordance with known aircraft endurance limits. For the elevation channel this is manifested as a normal acceleration limit.

The above example could be applied to the roll and heading channels also. For these channels the pilot transfer functions will produce suitable signals for the control of the aileron and rudder respectively.

This brief digression illustrates how the human transfer function is used in each channel of the pilot subroutine to control the
aircraft position and thus perform pursuit tracking. With these sections of the overall man-machine task described, the method used for the digital analysis of the human transfer function should be easier to understand.

The method used for evaluation after implementation of the coupler transfer functions was unique because of the tracking data which was used in the analysis. This data was obtained from a joint AFSC-TAC test program. The program, which was entitled Combat Hassle was conducted at Eglin Air Force Base in 1967 with the sole purpose of generating data for the evaluation of mathematical simulations. In the project, two fighter aircraft were flown in combat maneuvers and a complete set of radar data was generated. This data was then reduced into a statistically proper set of combat flights, some of which are shown in planar and three-dimensional form in Appendix I.

The method of evaluation incorporated Combat Hassle evader trajectories which were included in IMAGE by the use of the pre-programmed target trajectory feature of the flight path simulation. The human transfer function was allowed to act on this evasion trajectory in order to minimize the tracking error and to position the guns in order to fire. The flight was then analyzed from the viewpoint of total tracking error and minimum miss distance which occurred. Throughout the course of the investigation, emphasis was placed on developing improved human transfer functions that provided low minimum miss distances for all maneuvers of the evading aircraft.
SPECTRAL ANALYSIS

In the investigation of the characteristics of the pilot response and the systematic search for a pilot coupler transfer function, an analytical method was needed to help determine a suitable criterion for the study. The evaluations of the performance of the pilot simulation were complicated severely by the sheer volume of input data that a pilot must process during any given engagement. Further difficulties arose due to the fact that no two engagements were exactly the same. It was impossible to implement a pilot simulation and process all possible engagements through it. For this reason some method of extracting general pilot performance characteristics had to be devised.

It was concluded that these general performance characteristics would manifest themselves in the content of the pilot's output during an actual air-to-air engagement. A statistical analysis of the performance output obtained from the IMAGE simulation would delineate the pilots characteristics well enough to make a comparative study to the attacker data obtained from Combat Hassle.

The method of evaluation was then simply to subject the attacking aircraft maneuver obtained from the simulation to a series of spectral analysis operations in which the frequency content of the aircraft simulation could be compared to the frequency content of the data obtained from the Combat Hassle flight maneuvers. In this manner both the simulated attacker and the real attacker were subjected to the same realistic evasive maneuver for comparison purposes.
The tool for the analysis was a digital computer program capable of performing the desired spectral operations and plotting the results of these operations. The data used for the analysis was characterized as transient in nature. It represented a random physical phenomenon which could not be described by an explicit mathematical relationship because each observation of the phenomenon was unique. Because of this data characteristic, the collection, or ensemble, of all the data for a particular engagement was assembled and treated as a stochastic process. These stochastic processes were then analyzed in a statistical manner through the use of three basic tools of spectral analysis, namely,

1. Power spectral density function,
2. Cross-correlation functions, and the
3. Autocorrelation function.

Of the three operations performed in the digital spectral analysis the power spectral density function proved to be the most useful. Use of the power spectral density function described the frequency composition of the data in terms of the density of the data at each frequency. More simply, it furnished information concerning the amplitude and intensity of the data as a function of the frequency.

In the frequency range between \( f \) and \( f + \Delta f \), the power spectral density function is defined mathematically as:

\[
G_X(f) = \lim_{f \to 0} \lim_{T \to \infty} \frac{1}{(\Delta f)T} \int_0^T X^2(t,f,\Delta) dt \quad (IV-2)
\]
In equation (IV-2) $X(t,f,Af)$ is that portion of the data which falls in the frequency range $(f,f+Af)$. An example of data characterized by a narrow band of random noise and the resulting form of the power spectral density plot is illustrated in Figure 15.

The operation of describing the general dependence of the values obtained from the IMAGE simulation to the values obtained from Combat Hassle was performed by the cross-correlation function. The cross-correlation function $R_{xy}(T)$ is shown in equation form by:

$$R_{xy}(T) = \lim_{T \to \infty} \frac{1}{T} \int_{0}^{T} x(t) y(t+T) dt$$  \hspace{1cm} (IV-3)

The interpretation of a typical cross-correlation function, Figure 16, is that when the function is zero the sets of data being compared are completely unrelated and when the function has a large value, the sets of data are related to large degree with respect to frequency and time.

$R_x(T)$, the autocorrelation function, describes the general dependency of the values of the data obtained at any one particular time to the values of the data obtained at any other time. Therefore, the principal application for the autocorrelation function is to establish the influence of values at any time. In this manner the autocorrelation function clearly provides a useful tool for selecting deterministic data which might be masked in a random noise background. An illustration of the autocorrelation functions is shown in Figure 17 and the mathematical description of the function is given by
NARROW BAND RANDOM NOISE

RESULTING POWER SPECTRAL DENSITY

Figure 15  Power Spectral Density Function
Figure 16 Cross-Correlation Function
Figure 17 Autocorrelation Function
\[ R_x(T) = \lim_{T \to \infty} \frac{1}{T} \int_0^T x(t) x(t+T) dt \quad (IV-3) \]

In the actual digital implementation, this function is not calculated as such, but the relationship between the power spectral density function and the autocorrelation function is employed, by the use of a Fourier transform;

\[ C_x(f) = 2 \int_{-\infty}^{\infty} R_x(T) e^{-\alpha^2 \pi f^2} dT \quad (IV-4) \]

This relationship is possible to implement in the digital analysis through the use of the Cooley-Tukey fast Fourier transform which is designed to operate over a discrete function.

The data records from Combat Hassle representing the position coordinates of an attacking aircraft in a three dimensional system were presented at equal increments of time of 1/20 of a second. The physical maneuvers which they describe were random flight paths of short duration (usually of order 10-15 seconds) and consequently they were classified as transient, deterministic, and stationary data. Similarly the data from the IMAGE autopilot simulation were composed of random maneuvers of an attacking aircraft and they too could be classed in this group. By performing these spectral analysis operations on both data sets, they are transformed into a format which is very descriptive of the frequency characteristics of the pilot and aircraft during actual maneuvers. This transformation into the frequency domain presents a very straightforward method for determining the degree of similarity between two data sets.
It was concluded from this investigation that pilot parameter variations for the IMAGE simulation which are sufficiently identifiable in the power spectral density plot comparisons, enabled parameter ranges to be estimated. Further, a parametric variation was used, via the power spectral density comparisons, to delineate those pilot parameters having the most significant effect upon the performance of the actual aircraft.
OPTIMIZATION TECHNIQUE APPLIED TO AERIAL SIMULATION

The scheme of automatically varying the parameters was made possible through the implementation of Powell's technique to find the minimum of a function of several variables without calculating derivatives. The method of implementing Powell's optimization scheme into the fire control simulation is shown in Figure 18. The obvious feature of this diagram is that the optimization technique is not a subprogram of the fire control simulation; but rather, the fire control simulation, after the initialization portion becomes a sub-portion of the optimization scheme. The normal fire control integration loop appears as a subroutine for the optimization. This arrangement affords the flexibility of using the optimization scheme for optimizing parameters in any portion of the simulation.

Figure 18 illustrates how the optimization technique was utilized in the simulation in order to yield a method of automatic pilot parameter variation. Once the parameters to be optimized are selected (in this case the parameters chosen were the pilot gain and pilot lead time in the elevation, roll and heading channels) the inner
Figure 18 Optimization Control of the Fire Control Integration Loop
loop is traversed which controls the fire control optimization. As illustrated, this loop is comprised of the three following component systems:

1. Variation of Parameters
2. Fire Control Integration Loop
3. Evaluation of Error

The optimization loop determines the optimum value for each appropriate parameter of the human transfer function by performing a series of one dimensional searches in the function space of the aircraft performance. An independent search is performed for each parameter to be optimized with each search being accomplished by utilizing a rerun simulation technique. The technique requires the simulation to proceed for a small period of time in order to determine the performance of the aircraft for the particular parameter considered and then returning to the initial conditions and reflying that portion of the simulation and continuing until an optimum set of parameters are determined, for that particular flight path time increment. Once a set of optimum parameters are determined, the next period of time is considered utilizing this same procedure.

Consider the two dimensional optimization of the pilot gain and pilot lead time in the elevation channel as an example. For this case, reference should be made to Figure 9 shown previously. Initially a search is performed along a coordinate direction until a value for the pilot gain is determined which yields a relative minimum value for the performance criterion. This requires the
simulation to be performed each time an increment of the parameter value is made in determining the relative minimum. Once this is accomplished the pilot lead time is then determined in the same manner by performing a search in the other coordinate direction. After these two searches are accomplished an average search based on these searches is performed in the function space to determine a better approximation to the optimum values of gain and lead time. This process is then repeated until the approximations to the optimum converge to an absolute minimum value of the performance criterion for the particular evasion tactic.

Aside from the subroutines already in the fire control simulation, (Figure 12), four subprograms were written to perform the main portion of the necessary optimization tasks. They are:

1. PAROPT (Parameter Optimization),
2. MNWD1A (Minimization Without Derivatives),
3. RLMN1B (Relative Minimum), and
4. SUMERQ (Error Summation).

The task of selecting, setting, and varying the variables to be optimized as well as the optimization default is the function of subroutine PAROPT, (Parameter Optimization). This subroutine is illustrated in Figure 19. Initially a decision to optimize based on input information is made in this subroutine. If a non-varying parameter simulation is desired, proper indicators are set and the optimum fixed parameters encountered in the Fire Control simulation are employed. However, if parameters are to be optimized
Figure 19 Parameter Optimization Subroutine
Figure 19 Con't Parameter Optimization Subroutine
the scheme initially stores the length of time the optimization is to proceed and the initial values of the parameters. The optimization variables are constrained by upper and lower limits determined by the input data, so a feature was added which allows the procedure to determine if a variable has achieved a limiting value and if so, remove it from the list of variables being changed for a certain predetermined number of integration time steps. Obviously this feature was required in order to allow a certain degree of flexibility in controlling the speed of computation when a large number of variables are involved. Once the variables are set into the optimization variable array, successive steps in simulation time are taken until the cutoff time is reached.

In normal operation, the task of determining the directions of the n search vectors for the optimization is accomplished by subroutine MNWD1A (Minimization Without Derivatives). This subroutine which is illustrated in Figure 20, is Powell's non-gradient method with slight modifications. In this subroutine all necessary counters are initially set and the n base vectors (coordinate directions) are chosen for the initial linearly independent directions. N-successive minimizations are then performed along these coordinate directions and an average direction is computed from these calculations. Along this direction a minimization is then performed. If this newly determined approximation for the optimum value does not meet convergence properties the subroutine then determines a new set of N-linearly independent search directions and performs
SUBROUTINE MNWdia

SET COUNTERS

SET BASE VECTORS

TAKE N SUCCESSIVE STEPS ALONG BASE VECTORS

COMPUTE AVERAGE STEP TAKEN

CONVERGENCE

NO YES

NET STEP

A B C D

Figure 20 Non-Derivative Minimization Subroutine
Figure 20 Con't Non-Derivative Minimization Subroutine
the same procedure over again. If at any time convergence properties are satisfied the value of the variables for optimum operation are returned to the fire control simulation.

The process of determining a relative minimum along a line is the task assigned to subroutine RLMN1B (Relative Minimum). This subroutine illustrated in Figure 21 lacks the precision found in some relative minimum procedures. This was done in the interest of acquiring computational speed; but, the compromise did not seriously affect the final accuracy of the solution. This was due to large number of searches that were performed to arrive at the desired convergence properties.

Initially the relative minimum subroutine sets an increment in the parameter vector which is to be optimized. This increment is characterized as the optimization step size. At this point the performance is evaluated. If this value is found to be smaller than the initialization point, the process updates itself and continues. If the value is found to be larger than the initialization point, the direction of search is changed before the process is updated. The actual stepping procedure is accomplished by evaluation of the error and doubling the step size until a minimum is reached or passed. At this point the step factor for the search vector is set equal to the length of step found in the relative minimum subroutine.

The subroutine which determines the error performance is SUMERQ (summation of per step error evaluations). This subroutine is
SUBROUTINE RLMN1B

SET STEP SIZE

INCREMENT VECTOR TO BE OPTIMIZED

EVALUATE ERROR

YES
ERROR

NO

RESET INITIAL POINT AND STEP

EVALUATE ERROR

CHANCE DIRECTION OF STEP

Figure 21 Relative Minimum Subroutine
Figure 21 Con't Relative Minimum Subroutine
illustrated in Figure 22. At each step in time, subroutine SUMERQ is called and the range performance factor as well as the tracking error is stored. The final summation of these quantities comprise the performance criterion and is used as the value of the performance error.
Figure 22 Summation of Per Step Error Evaluation Subroutine
SECTION VI
INVESTIGATION RESULTS

DIGITAL COMPARISONS

The objective of the investigation was to determine a suitable human operator transfer function which would perform pursuit tracking tasks when subjected to random evader tactics, and optimize parameters of this transfer function for a variety of evader tactics.

The initial work in establishing a suitable transfer function was the implementation of the optimization scheme to the original IMAGE simulation. In the original version of IMAGE, the fire control portion would be operated by using what was considered to be the optimum fixed parameters for the human transfer function. Previous studies for the most part, implemented the human operator by the use of a gain constant.

Initial comparisons were made of the optimization scheme with the previous cases which were considered in IMAGE. Figure 23 shows the total tracking error in degrees as a function of time for a two G maneuver in which the optimum fixed parameters were used. In this engagement the total tracking error remained below two degrees and the guns were firing for the total length of the engagement. Until
TOTAL TRACKING ERROR (DEGREES)

CASE 4.02
OPTIMUM FIXED PARAMETERS

ENGAGEMENT TIME (SECONDS)

Figure 23 Optimum Fixed Parameters for 2-G Maneuver
this study, this was the most consistent and accurate pursuit tracking that was accomplished in IMAGE because the human transfer function was unable to adapt.

A plot of the total tracking error for the same maneuver is shown in Figure 24, except that in this case the gain parameter for the human operator was varied by the optimization process. The value of the result should be stressed. Though the optimization process did not change the shape of the entire curve, (it would not be expected if the fixed parameters were really optimum!), it did improve the tracking ability of the human pilot model to a certain degree. This indicated that the new scheme was capable of producing pursuit tracking which was better than a corresponding fixed parameter scheme. It also indicated that the need for determining the fixed parameters (a rather difficult and lengthy task) was not necessary.

With the preliminary results clearly indicating that the proposed scheme for changing the dynamic characteristics of the pilot model was an improvement over past methods, a further attempt was made to modify the human transfer function so as to more realistically simulate human behavior.

In the next series of evaluations, the human model was expanded from a pure gain in the elevation and traverse channels to a transfer function of the form:

\[
\frac{K_p(T_L + 1)}{(T_I + 1)(T_N + 1)}
\]

(VI-1)
CASE 4.02
TWO PARAMETER OPTIMIZATION
ELEVATION NUMERATOR
NO TIME LAGS

Figure 24 Two Parameter Optimization for 2-G Maneuver
In this case the pilot gain, $K_p$, and the pilot lead time, $T_L$, were allowed to vary in both the elevation and traverse channels. The lag time and the neuromuscular time were set to consistent constant values.

Again the final results clearly indicated that progress was being made in the right direction. A plot of the total tracking error for the same evasive maneuver with the fixed gain parameter is shown in Figure 25. The plot of the total tracking error obtained from the four parameter optimization with the lags included in the model is shown in Figure 26. In this comparison there is an increase in error when the optimization is employed. The increase in error is due to the lag involved in the model, however, lag in the model is considered to be a closer approximation to actual human behavior. It should also be noted that these series of evaluations indicate the ability of the model to track for extended periods of time.

Assuming a relative success with that particular evasive maneuver, a one G non-maneuvering target was considered. This was chosen to form a basis of comparison with previous IMAGE simulations. In this engagement a significant decrease in the total tracking error occurred when the four parameter optimization was applied. The illustration of the total tracking error for the fixed parameter gain versus the optimization scheme appears in Figure 27.

It should be noted that the constraints on the pilot parameters for these evaluations did conform to the state-of-the-art simulator data for a human operator nulling tracking error by stick rotation indicated in Table III.
Figure 25  Optimum Fixed Parameters for 2-G Maneuver
CASE 4.02
FOUR PARAMETER OPTIMIZATION
ELEVATION AND BANK NUMERATORS
TIME LAGS INCLUDED

Figure 26 Four Parameter Optimization with Lags for 2-G Maneuver
CASE 3.01
OPTIMUM FIXED PARAMETERS
VERSUS
FOUR PARAMETER OPTIMIZATION
ELEVATION AND ROLL CHANNELS
WITH LAGS

Figure 27 Optimum Fixed Parameter versus Four Parameter Optimization for IMAGE Case 3.01
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>Pilot Gain</td>
<td>0.00001 to 100.</td>
</tr>
<tr>
<td>$T_D$</td>
<td>Pilot Dead Time (Seconds)</td>
<td>0.1 to 0.5</td>
</tr>
<tr>
<td>$T_L$</td>
<td>Pilot Lead Time (Seconds)</td>
<td>0.00001 to 2.5</td>
</tr>
<tr>
<td>$T_N$</td>
<td>Neurovascular Lag Time (Seconds)</td>
<td>0.1 to 0.16</td>
</tr>
<tr>
<td>$T_L$</td>
<td>Pilot Lag Time (Seconds)</td>
<td>0.01 to 1.</td>
</tr>
</tbody>
</table>
The pursuit tracking tasks which the one G and the two G maneuvers presented to the model could not be considered as random evader tactics but were used because the cases had been well documented for fixed parameter optimum values. In both cases a four parameter optimization of the coupler transfer functions which included the appropriate lag term was considered sufficient. For this reason these basic maneuvers were abandoned and the more realistic maneuvers which were obtained from Project Combat Hassle were incorporated into the simulation.

After initial consideration of one of the Hassle maneuvers, it became apparent that a four parameter optimization could no longer produce a sufficiently realistic small value for the total tracking error. The heading command coupler transfer function which controls rudder deflection had to be included as part of the optimization scheme. The attempt to null tracking error for Case 3 Combat Hassle with a four parameter optimization is shown in Figure 28. Obviously the aircraft was uncontrollable. The ability of the four parameter optimization to be sufficient for the one and the two G maneuvers was accredited to the fact that these basic maneuvers were only in two dimensions, whereas flight maneuvers from Hassle were considered to be realistic combat engagements, including motion in three dimensions.

At this point a six parameter optimization was utilized and the results for Case 3 of Combat Hassle are illustrated in Figure 29. The parameters which were optimized were the pilot gain and pilot
Figure 28  Four Parameter Optimization with Lags for
Hassle Case 3
HASSLE CASE 3
ENGAGEMENT 3-1 DEC. 6, 1967
SIX PARAMETER OPTIMIZATION
ELEVATION, ROLL, AND HEADING CHANNELS
WITH LAGS
GAIN 1. TO 100. LEAD .2 TO 2.5

TOTAL TRACKING ERROR (DEGREES)

ENGAGEMENT TIME (SECONDS)

Figure 29 Six Parameter Optimization with Lags for Hassle Case 3
lead time constant in the elevation, bank, and heading channels. The minimizing of tracking error results were good, however, it was noted at this point that during the process of minimizing the total tracking error, the roll rate of the aircraft was becoming excessive. Until this unstable situation was noticed the pilot gain constant was allowed to vary between one and one hundred. At the same time the pilot lead time was allowed to vary between one tenth of a second and two and one half seconds. It became necessary to again evaluate the parameter limits of the transfer function. This was accomplished by the use of a spectral analysis program on the output of Hassle data and established a more realistic range of values.

At this point the maximum upper limit on the pilot gain was decreased to fifty. In this case the tracking ability was satisfactory; however, the roll rate did approach a maximum value of eighty degrees per second which is larger than the desired rate. A plot of the total tracking error versus engagement time is shown in Figure 30.

The parametric variation for the six parameter optimization, Figure 31, clearly revealed the reason the four parameter optimization was not sufficient for the Hassle Case 3 maneuver. The variations show that the heading channel contains the more severe channel dynamics. Without the large transfer function adjustment in this channel, the rudder deflection was not sufficient to maintain pursuit tracking.
HASSLE CASE 3
ENGAGEMENT 3-1 DEC. 6, 1967
SIX PARAMETER OPTIMIZATION
ELEVATION, ROLL, HEADING CHANNELS
WITH LAGS
GAIN 1. TO 50. LEAD .2 TO 2.5

Figure 30 Six Parameter Optimization with Lags for
Hassle Case 3
PARAMETRIC EFFECTS IN OPTIMIZATION OF AUTOPilot PARAMETERS FOR TEST CASE 3 HASSLE

![Bar chart showing the parametric effects for six parameter optimization utilizing Hassle Case 3.](image)

Figure 31 Parametric Effects for Six Parameter Optimization Utilizing Hassle Case 3
The investigation at this point led to the following general observations:

1. When necessary, the human operator seeks to obtain as much lead in a particular channel as is feasibly possible.
2. Pilot gain is the most critical parameter in the model, unless the lead term is very large.
3. If channel dynamics are not severe an essentially optimum fixed parameter is established.

The interrelation between the parameter variation and the total tracking error for the engagement can be obtained by observing the Figures 30 and 31. Prior to the time 261 seconds, the engagement proceeded with the best parameters to minimize the tracking error. At the time 261 seconds, the aircraft dynamics were such that the parameters had to change in order to keep the tracking error from increasing drastically. To accomplish this, lead in the elevation channel was increased and the corresponding gain in the heading channel. The effect is noted at the time 261.5 seconds. Again at time 262.5 the parameters are noticeably adjusted. Gain in both the heading and elevation channels and lead in the elevation and heading channels are increased. Their effect on minimizing the total tracking error for the engagement is reflected at time 262.8 seconds. The flight then proceeds in an acceptable manner until time 264 seconds. At this time the high gain in the elevation channel is no longer necessary. Because of this action and the changing flight dynamics which cause an increase in tracking error,
the parameters again make a noticeable adjustment at time 265 seconds. It is at this point in the engagement that the lead terms in the elevation and roll channels are increased to their boundaries.

In addition to further justification for the six parameter optimization, this illustration of the parametric variation showed that the aircraft instability developed when the terms were at their upper boundaries. In particular instability occurs when the pilot transfer function tries to anticipate a long period in advance. It was concluded that the instability could be avoided by lowering the maximum values that could be achieved by the pilot gain and pilot lead time.

Figure 32 illustrates the next step in the approach. In this case the pilot gain ranged from one to fifty and the pilot lead time ranged from .0001 seconds to one second. For the case considered, total tracking error increased but the maximum roll rate of the aircraft was reduced. Because of the reduction in lead time imposed by the boundaries, the gain parameters began showing a predominant role in the relationship between the parametric variations as illustrated in Figure 33, and the total tracking error for the engagement. Quite apparent is the increase in pilot gain in the heading channel at time 261 seconds and also the decrease in pilot gain in the elevation channel at time 262.5 seconds. The increase at time 263.5 seconds by the pilot gain in the elevation channel is accompanied by a corresponding increase of the pilot gain in the roll channel. The results of all adjustments can be observed from the
HASSLE CASE 3
ENGAGEMENT 3-1 DEC. 6, 1967
SIX PARAMETER OPTIMIZATION
ELEVATION, ROLL, AND HEADING CHANNELS WITH LAGS
GAIN 1. TO 50. LEAD .0001 TO 1.

Figure 32 Six Parameter Optimization with Lags for Hassle Case 3
PARAMETRIC EFFECTS IN OPTIMIZATION OF AUTOPILOT PARAMETERS FOR TEST CASE 3 HASSLE

Figure 33 Parametric Effects for Six Parameter Optimization Utilizing Hassle Case 3
total tracking error illustration of Figure 32. The lead parameters are the predominant factors in the parametric variation. Though the lead parameters are the most anticipatory in nature, they can be controlled to reflect aircraft stability and the pilot gain adjusted sufficiently to provide acceptable control of the aircraft in the pursuit tracking configuration. Furthermore these lead parameters do not necessarily remain on their maximum boundaries in an effort to reduce the total tracking error. For example, at time 265 seconds the elevation and the heading lead times are increased to their maximum boundary and the effectiveness of the pilot's anticipatory action is thus illustrated.

In a further effort to improve the handling qualities of the aircraft, the maximum value of the pilot gain was reduced to thirty. This case as shown in Figure 34 appears to correct the stability problem. The maximum value for the aircraft roll rate for this case was twenty-five degrees per second. This rate is well within a tolerable roll rate range. The parametric variation in this case is shown in Figure 35.

To proceed to develop a more suitable transfer function, a 0.2 second reaction dead time was incorporated to the existing model. The results for IMAGE Case 4.02, Hassle Case 3, Hassle Case 1, and IMAGE Case 3.01 are shown in Figures 36, 37, 38, and 39 respectively.

When the six parameter optimization with the fully expanded pilot model was applied to IMAGE Case 4.02 the error results were very low. Ninety percent of the tracking error over the flight portion investigated was below one degree and the largest error was
HASSLE CASE 3
ENGAGEMENT 3-1 DEC. 6, 1967
SIX PARAMETERS OPTIMIZATION
ELEVATION, ROLL, AND HEADING CHANNELS
WITH LAGS
GAIN .0001 TO 30. LEAD .0001 TO 1.

Figure 34 Six Parameter Optimization with Lags for Hassle Case 3
PARAMETRIC EFFECTS IN OPTIMIZATION OF AUTOPILOT PARAMETERS FOR TEST CASE 3 HASSLE

- ELEVATION CHANNEL GAIN
- ELEVATION CHANNEL LEAD
- TRAVERSE CHANNEL GAIN
- TRAVERSE CHANNEL LEAD
- HEADING CHANNEL GAIN
- HEADING CHANNEL LEAD

ENGAGEMENT TIME (SECONDS)

Figure 35 Parametric Effects for Six Parameter Optimization Utilizing Hassle Case 3
Figure 36 Six Parameter Optimization with Lags and Reaction Dead Time for IMAGE Case 4.02
Figure 37  Six Parameter Optimization with Lags and Reaction
Dead Time for Hassle Case 3
HASSLE CASE I
SIX PARAMETER OPTIMIZATION
WITH PILOT DEAD TIME
TIME LAGS

Gain .00001 to 50. lead .00001 to 1.

Figure 38 Six Parameter Optimization with Lags and Reaction
Dead Time for Hassle Case 1
Figure 39 Six Parameter Optimization With Lags and Reaction
Dead Time for IMAGE Case 3.01
less than one and one half degrees. A further evaluation performed in the terminal effectiveness portion of the simulation for this case showed the minimum miss distance for the optimization scheme to be reduced to a value of three feet, as illustrated in Figure 40.

The parametric variation for Case 4.02 is shown in Figure 41 and illustrates the reasoning behind the selection of the original optimum fixed parameters used in the simulation. For the first six seconds of the engagement the parameters in the elevation channel are essentially constant with the heading channel lead time negligible. However, the inability of these fixed optimum parameters to perform for extended periods of time is apparent at time 266 seconds. At this point, the original optimum fixed parameters must adjust to account for the aircraft dynamics. Due to the previous fixed parameter assumption an acceptable fight regime would not be possible after about six seconds of engagement time. An increase in lead in the elevation channel at that time would be required to decrease the total tracking error.

The parametric variation illustrated for the Hassle Case 3 evasive maneuver is shown in Figure 42. The variations are basically the same as was observed in the previous Hassle cases without pilot reaction dead time. The only noticeable difference is the reduction of the maximum values which each parameter achieved during the course of the engagement.

The non-maneuvering target evasion that was implemented in IMAGE Case 3.01 revealed some interesting features relevant to the original fixed parameter cases. The parameter variation in Figure 43
Figure 40 Minimum Miss Distance for Fixed Parameter versus Optimum Parameter for IMAGE Case 4.02
PARAMETRIC EFFECTS IN OPTIMIZATION OF AUTOPILOT PARAMETERS FOR TEST CASE 4.02 IMAGE

Figure 41 Parametric Effects for Six Parameter Optimization Utilizing IMAGE Case 4.02
PARAMETRIC EFFECTS IN OPTIMIZATION OF AUTOPILOT PARAMETERS FOR TEST CASE 3 HASSLE

Figure 42 Parametric Effects for Six Parameter Optimization Utilizing Hassle Case 3
PARAMETRIC EFFECTS IN OPTIMIZATION OF AUTOPILOT PARAMETERS FOR TEST CASE 3.01 IMAGE

Figure 43. Parametric Effects for Six Parameter Optimization Utilizing IMAGE Case 3.01
shows that for the first three seconds the rudder deflection was not necessary to maintain pursuit tracking. The traverse channel was essentially the same for this period and the elevation channel with the exception of the need for more lead was also essentially the same as the original optimum fixed parameters. Figure I-2 shows that after 14 seconds of the engagement the attacker was not able to pursue adequately because of these fixed parameters. The changes in the parameters to account for this are shown after 15 seconds of the engagement. The parameters are adjusted for the evasive maneuver and the deviation was corrected, thus yielding an acceptable pursuit tracking engagement. This period is reflected as a total tracking error of approximately .25 degrees in Figure 39.

SPECTRAL COMPARISONS

In order to supply information concerning the appropriate limits to be applied to the variable parameters of the human transfer function as well as support the optimization procedure, a series of spectral operations were performed on the data from Project Combat Hassle Case 3. In this analysis the attacker data generated in IMAGE was compared to the attacker data obtained from Hassle when both the simulated and the real aircraft were subjected to the same random evasive maneuver.

To determine the approximate range of values for the pilot gain and pilot lead time, a plot of the power spectral density function were made. The power spectrum functions were obtained by letting the pilot gain in one channel vary while holding the pilot lead
time constant. The analysis was performed in the three control channels by a series of parameter variations.

As an example, consider the elevation channel. First the pilot gain in this channel was allowed to vary while all the remaining pilot transfer function parameters were held constant. This produced a series of power spectral density plots for varying pilot gain in the elevation channel. A typical plot of this type is shown in Figure 44. These plots supply information concerning the energy amplitudes as a function of frequency of the attacking aircraft position data. This particular plot reveals that all the performance characteristics of the aircraft, which are directly a function of the pilot's actions, occur at less than three hertz in the elevation channel. The remainder of the plot represents amplitudes at frequencies greater than three hertz are constant and similar to white noise data. This might be attributed to the radar. The next series of parameter variations allowed the lead time in the elevation channel to vary while all the remaining parameters were held fixed. In the same manner as before, a series of parameter variation spectral density plots were produced.

This type of parameter variation was utilized on every parameter in each channel while a further variation of the constant values was also utilized to determine the acceptable range of pilot transfer function parameters. When each parameter had been varied throughout its range as projected by simulator data, the plots were grouped according to the three pilot transfer function channels and plotted
Figure 44 Elevation Channel for Variation of Pilot Gain Parameter
together. In this manner it could be seen how each variation of the parameters affected each control channel.

As a means of evaluating which set of parameters were most consistent with human pilots, the series of plots were then compared to the power spectral density plots of the Combat Hassle attacking aircraft control channels. In this manner a realistic range for the pilot transfer function parameters could be established. As anticipated the results from the spectral analysis supported the optimization results. Based on the parameters with constant values, the investigation revealed that the pilot gain in the elevation channel should range between a very small positive value and a maximum value of approximately fifty. The pilot gain in the traverse channel should have a range from a very small value to a maximum of approximately fifty. Also, the pilot lead time should range up from a small positive value and have a maximum value of about one and one-half seconds.
SECTION VII
CONCLUSIONS

This investigation was conducted in order to determine a realistic model for a human operator. To evaluate the model, a digital simulation of series of aerial combat engagements in which the model was placed in the role of an attacker for the aircraft fighter simulation were utilized. As a result of investigating the ability of the model to perform pursuit tracking tasks when subjected to random evader tactics the following was concluded.

1. Human Transfer Function Form:

A transfer function model of the form:

\[
\frac{-T^D K e^{T_D (T_L + 1)}}{(T_A + 1)(T_N + 1)}
\]  \hspace{1cm} (VII-1)

is sufficient to handle the random pursuit tracking tasks to which it was subjected while illustrating the dynamic characteristics of human behavior. This form of the human transfer function model has been substantiated by simulator data collected by psychologists who conducted tasks which were arranged to utilize constant parameters in the transfer function...
model. This investigation showed that this form of the model could be applied to tasks in which the pilot parameters are capable of varying and thus allowing the dynamic characteristics of the human operator to become more realistic.

2. Variable Parameter Range

A suitable range for the variable parameters in the human transfer function has been established. The parameter variations for the three channels are as follows:

**Elevation Channel**

- Pilot Gain: 0.00001 to 50.
- Pilot Lead Time: 0.00001 to 1.

**Bank Channel**

- Pilot Gain: 0.00001 to 30.
- Pilot Lead Time: 0.00001 to 1.

**Heading Channel**

- Pilot Gain: 0.0000 to 50.
- Pilot Lead Time: 0.00001 to 1.

These parameters were established while the remaining parameters in each channel were held to fixed values consistent with current state-of-the-art evaluations. The constant values were:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Pilot Reaction Dead Time</td>
<td>.2 seconds</td>
</tr>
<tr>
<td>(b) Pilot Neuromuscular Lag Time</td>
<td>.1 seconds</td>
</tr>
<tr>
<td>(c) Pilot Lag Time</td>
<td>.1 seconds</td>
</tr>
</tbody>
</table>
3. Optimization Technique

The basic method developed by M. J. D. Powell provides the best means for adjusting the variable parameters of the human transfer function model in order to achieve the desired man-machine tasks in the most direct way. This method of parameter optimization is most suited for automatic parameter adjustment because it does not require the calculation of derivatives and the number of function evaluations it does require is reduced for problems with large dimensions.

4. Performance Criterion

For the pursuit tracking task the maximum probability of kill error criterion yielded the best tracking performance. Any optimization technique is only as good as the performance criterion which it utilizes. The combination of range and angle off which was utilized takes into account optimum attack logic for both long and short range tactics and provides a suitable criterion for aerial combat.

5. Extended Tracking Periods

For all the engagements considered it was concluded that the automatic adjustment of the pilot transfer function parameters would extend the length of the fire control flight regime.
6. Significant Parameter Effects

From the parametric variations observed from the digital comparison and the power spectral density comparisons, the pilot transfer function parameters which have the most significant effect upon the overall performance of the aircraft were determined.

Recommendations for Future Research

1. Further Implementations

The next direction in which efforts in the area of human operator behavior should be directed is further task implementations. Utilizing a suitable error criterion, the automatic adjustment techniques of varying the parameters of the human operator transfer function should be applied to other man-machine tasks.

2. Predictive Behavior

The presented simulation could be improved in a manner which would simulate the predictive behavior of the human pilot. Instead of operating on the maximum probability of kill criterion, a first or second order prediction scheme could be utilized to determine the necessary future position of the attacking aircraft based on the predicted position of the evading aircraft. The pilot transfer function could then be adjusted to control the aircraft utilizing a criterion composed of minimizing the difference in the actual attacking aircraft position and the necessary position as determined from the predictive scheme.
APPENDIX I

The following are the plots of the trajectories used in the analysis; it includes:

1. IMAGE Case 3.01
2. IMAGE Case 4.02
3. Hassle Case 1
4. Hassle Case 3
Case 4.02
Time (sec.) 20-30
Horizontal 2-G Turn

Figure I-1 IMAGE Case 4.02 Horizontal 2-G Turn
Case 3.01

Time (sec.) 12-22

Horizontal Acceleration

ATTACKER

EVADER

Figure I-2 IMAGE Case 3.01 Horizontal Non-Maneuvering Evader
Figure I-3  Hassle Case 1  X-Z Plane for Attacker
Figure I-4  Hassle Case 1 X-Y Plane for Attacker
Figure I-5 Hassle Case 1 X-Z Plane for Evader
HASSLE CASE 1 EVADER
X-Y PLANE

Figure I-6 Hassle Case 1 X-Y Plane for Evader
Figure I-7 Hassle Case 3 X-Z Plane for Attacker
Figure I-8  Hassle Case 3  X-Y Plane for Attacker
Figure I-9 Hassel Case 3 X-Z Plane for Evader
Figure I-10 Hassle Case 3 X-Y Plane for Evader
Figure I-11  Hassle Case 1  Three Dimensional Attacker
Figure I-12 Hassle Case 1 Three Dimensional Evader
HASSLE CASE 3
ATTACKER
3-D PLOT

Figure I-13 Hassle Case 3 Three Dimensional Attacker
Figure I-14 Hassle Case 3 Three Dimensional Evader
REFERENCES


VITA

The author was born in New Orleans, Louisiana on August 14, 1944. His elementary education was received from Holy Trinity Catholic grammar school in New Orleans. The author was included in the June 1962 graduation exercises at St. Aloysius High School also in New Orleans.

His undergraduate work was at Louisiana State University graduating with a Bachelor of Science degree in Mechanical Engineering in January 1967. At that time he was granted a graduate assistantship by the Department of Mechanical Engineering of the University. He completed the requirements for the Master of Science degree in Mechanical Engineering at the University in August 1968.

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Candidate: Mario Joseph Caluda, Jr.
Major Field: Mechanical Engineering
Title of Thesis: A Human Model Which Optimizes Pursuit Tracking

Approved:

[Signatures]

Major Professor and Chairman
Dean of the Graduate School

EXAMINING COMMITTEE:

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Date of Examination:
March 8, 1971