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Pilot fatigue detection using aircraft state variables

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Pilot Fatigue Detection Using Aircraft State Variables

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College of Engineering and Mineral Resources
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ABSTRACT

Pilot Fatigue Detection Using Aircraft State Variables

Benjamin L. Smith

Pilot fatigue has been proven to be the cause of many aviation accidents. Fatigue introduces error into the pilot's inputs, which can potentially lead to accidents. To date, fatigue has been widely researched through physiological variables and sleep studies. Often, systems monitoring physiological variables would require constant physical contact with the pilot during flight. This arrangement could be cumbersome to pilots, and may hinder their flying ability even more. These systems will also add unnecessary weight to the aircraft, which could lead to increases in fuel consumption. Sleep studies have been investigated in an attempt to determine causes of pilot fatigue based on the amount and quality of sleep they have received pre-flight, but they only serve for fatigue prevention purposes.

The main objective of this research effort is to show that separation between 'rested' and 'tired' pilot conditions can be put into evidence using parameters based on aircraft state and control variables and to design a fatigue detection scheme to determine the 'on-line' state of the pilot for a set of typical maneuvers.

Five pilots were instructed to fly a 6 degrees-of-freedom flight simulator through a given flight scenario under 'rested' and 'tired' conditions. State and control variables such as aircraft roll rate, angle of attack, elevator deflection, and others were recorded during flight. The desired values of these variables were determined depending on what maneuver the pilot was trying to accomplish. Steady state flight conditions and doublet inputs in still air and turbulence were considered in this study. Tracking errors were defined as the difference between the actual variable value and the desired value. Standard deviation and mean of the tracking errors were considered as candidate fatigue detectors and their performance was analyzed. The most promising detectors were then used to define composite detection parameters as weighted sums.

Two detection schemes were designed to determine the 'rested' or 'tired' state of the pilot based on comparing the composite parameter values to a threshold. The first scheme used heuristic and binary logic to define a series of rules hard coded through 'if else' statements capable of determining the pilot's condition. The second detection scheme relied on fuzzy logic to make a 'rested' or 'tired' determination. Results showed that both schemes were capable of correctly classifying the condition of the pilot for many maneuvers. The detection schemes performed the best for the maneuvers performed in still air, but the detection rate was reduced when severe turbulence was present. A third approach of fatigue detection was investigated through implementation of a fuzzy neural network, and positive preliminary results deemed this method worthy of further exploration.

The analysis in this study presented compelling evidence that fatigue detection can be accomplished through the monitoring of aircraft state variables. Further research into using these detection schemes in conjunction with a flight compensation system may prove to be a viable, cost-effective intervention for reducing the number of accidents attributed to pilot fatigue.

ACKNOWLEDGEMENTS

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Nomenclature

Symbol	Description	Units
English		
V	Aircraft velocity	knots
p	Roll rate	rad/s
q	Pitch rate	rad/s
r	Yaw rate	rad/s
ail_y	Aileron pilot input	volts
rud_y	Rudder pilot input	volts
$elev_y$	Elevator pilot input	volts
Greek		
α	Angle of attack	degrees
β	Side-slip angle	degrees
φ	Roll angle	degrees
θ	Pitch angle	degrees
ψ	Yaw angle	degrees
Acronym		
CP	Composite Parameter	
SLF	Steady Level Flight	
T45	Turn with 45° Bank Angle	
T5	Turn with 5° Bank Angle	
PD	Pitch Doublet	
RD	Roll Doublet	
GUI	Graphical User Interface	
AGL	Above Ground Level	

Chapter 1

Introduction

According to the definition[1] by the International Civil Aviation Organization (ICAO), *"fatigue may be considered to be a condition reflecting inadequate rest, as well as a collection of symptoms associated with displaced or disturbed biological rhythms."* In the presence of fatigue, a pilot's ability to carry out otherwise normal functions is reduced. Fatigue negatively impacts physical and mental processes such as muscular coordination, sensorial perception, response to stimuli, memory retrieval, decision making, situational awareness, motivation, error management, and adaptability[2]. Recent studies have shown that there is a positive correlation between pilot fatigue and aircraft accident rates.

While most research has focused on studying physiological characteristics of pilots to combat fatigue related accidents, it may be difficult to implement such a method due to space constraints on added equipment and the need for constant physical contact with the pilot. As an example, the constant physical contact could potentially interfere with a pilot's G-suit, which may reduce his performance level even further.

To date, there have been no known studies related to pilot fatigue that involve monitoring aircraft state and control variables as fatigue detectors. These variables are already typically measured on board aircraft for control and navigational purposes which would provide a solution to the physical contact issue arising from measuring physiological characteristics. Such state variables would include roll, pitch, and yaw attitude angles, angle of attack, and velocity. The control variables would include deflection of the yoke and pedals. The hypothesis is that the reduced performance of the pilot due to fatigue can be captured through all or at least some of these state and control variables. For example, it would be expected that when trying to keep the aircraft on a steady level heading in the presence of fatigue the pilot would have to provide more compensation than normal. The additional compensation would be evident in the state and control variables making them good candidates as fatigue detectors.

The project called upon five volunteer West Virginia University aerospace engineering students with piloting experience to fly a pre-specified flight scenario in a 6 degrees-of-freedom flight simulator when they were considered 'rested' and 'tired'. The state and control variables mentioned above, along with others, were recorded but only three of the pilots' data were used for analysis purposes. The other two pilots' data was used to validate the findings from the first three.

Within the flight scenario there were six different types of maneuvers that were analyzed separately including steady level flights, coordinated turns, roll and pitch doublets, steady level flights in high turbulence, and coordinated turns in high turbulence. Each variable's actual value was compared to its corresponding desired value based on the type of maneuver being performed, which was termed as tracking error. For example, during a steady level flight maneuver the pilot is trying to keep the aircraft on a straight and level heading at a desired speed. Therefore, with the exception of velocity, all other variables should be kept at zero value. In the case of velocity the tracking error becomes the difference between the desired velocity called for in the flight scenario and the actual

speed of the aircraft. As for other states such as roll attitude angle the desired value would be zero as the pilot is trying to keep the aircraft as level as possible.

Standard deviation and mean were then calculated for each state and control variable's tracking error. The standard deviation of the tracking errors quantified how much compensation the pilot had to provide to keep the aircraft on course. The mean of the tracking error was used to quantify the amplitude of error of the pilot's performance. This process was completed during each maneuver and for both 'tired' and 'rested' conditions of the pilot in the attempt to show that standard deviation and mean values calculated when the pilot was 'tired' were in fact higher in magnitude as compared to when the pilot was 'rested'.

The variables that showed the most consistent 'rested' to 'tired' increase of standard deviation and/or mean were then considered the best fatigue detectors for the given maneuver. These variables were then compiled in composite parameters as a weighted sum. Higher weights were assigned to the variables that showed the most increase in amplitude of their corresponding standard deviation and/or mean value. The reason for the use of a composite parameter was based upon the hypothesis that even if one state or control variable's standard deviation and/or mean did not show an increase, the increase of standard deviation and/or mean of the other variables would compensate for it. As a result the composite parameter would then separate the 'rested' and 'tired' data such that the amplitude of the composite parameter from the 'tired' data would be higher than that of the 'rested' data.

Two fatigue detection schemes were designed to use the composite parameter's output in order to make either 'rested' or 'tired' determination of the pilot's condition. Each scheme would compare the composite parameter's value to a threshold. When the value of the composite parameter went above the threshold the schemes would consider the pilot 'tired'. Likewise if the composite parameter's value was below the threshold the scheme would consider the pilot 'rested'. The overall difference between the two schemes was in their ability to handle situations when the composite parameter's value crossed the threshold for only a short time as happened during many maneuvers. If the values of the composite parameter were below the threshold for the entire maneuver, with the exception of a short period, it would be undesirable to have a 'tired' decision made as these few data points do not characterize the data as a whole.

As this approach has never been attempted, the background section will present typical research previously investigated related to pilot fatigue and their potential methods of preventing fatigue induced accidents. The background will also briefly discuss the aircraft control system.

The experimental procedure section will detail the complete experiment from setup to data collection including: a discussion of instructor pilot interviews, the flight simulator, test pilots, 'rested' and 'tired' classifications, details of the flight scenario, a complete list of state and control variables, and how the data was processed.

The methodology section will explain: details of the candidate fatigue detectors, individual parameters, and composite parameters and their implementation within the two detection schemes.

The results section will provide tables and graphs and an explanation regarding the performance of the composite parameters and the two fatigue detection schemes.

The conclusions section will detail a summary of the overall outcomes of the research effort.

The lessons learned section includes additional information that could aid further research efforts regarding the use of aircraft state and control variables as a method of pilot fatigue detection.

Chapter 2

Background

2.1 Fatigue Literature

"On August 18, 1993, at 16:56 eastern daylight time, a military contract flight crashed while attempting to land at the U.S. Naval Air Station, Guantanamo Bay, Cuba. The airplane, a Douglas DC-8-61 freighter, was destroyed by impact forces and fire. The three flight crewmembers sustained serious injuries. The National Transportation Safety Board (NTSB), an independent agency of the United States government, conducted an official investigation to determine the cause of the accident and make recommendations to prevent a recurrence. The individual crew members had an acute sleep loss (i.e., 5, 6, 8 hrs of daytime sleep) and were continuously awake 19, 21, and 23.5 hours prior to the accident…"

-Rosekind, Gregory, et.al.[3]

"Hundreds of pilots, mechanics and air-traffic controllers reported that fatigue led them to make mistakes on the job, including six cases where pilots fell asleep in mid-flight. The reports show that crews flew to the wrong altitude, botched landings and missed radio calls, according to an aviation safety database compiled by NASA. In one case, a pilot and co-pilot fell asleep while descending toward Dulles International Airport near Washington, D.C…"

-USA Today[4]

As these two quotes illustrate, fatigue is a leading cause of pilot error. These errors can lead to serious accidents and even death. Since fatigue continues to appear in accident reports as a probable cause, a substantial amount of research is being focused on its prevention and detection. In researching previous fatigue studies, the following three topics of investigation would more or less categorize all prior efforts: (1) Causes of Fatigue, (2) Mathematical Human Operator Models, and (3) Physiological Monitoring.

The National Aeronautics and Space Administration's (NASA) Ames Research Center developed the Fatigue/Jet Lag Program in 1980 in response to a congressional request. The program was created to collect information on fatigue, sleep, circadian rhythms, and performance in flight operations[5]. In 1999 the group changed its name to the Fatigue Countermeasures Group to emphasize more importance on combating fatigue. According to a speech given by Michael Mann at the NASA Hearing on Pilot Fatigue before the Aviation Subcommittee of the Committee on Transportation and Infrastructure on August 3, 1999…

"…there is a safety problem of uncertain magnitude, due to trans-meridian flying and a potential problem due to fatigue in association with various factors found in air transport operations. A NASA/FAA countermeasure study empirically demonstrated the effectiveness of a planned cockpit rest period in improving performance and alertness in long-haul flight operations." However, "given that fatigue is a safety issue in aviation, the next logical question is how to address it. Unfortunately, there is no one simple solution. Fatigue is a problem with diverse causes, requiring a multi-faceted and comprehensive yet integrated approach. Based on current research, such an approach should have at least the following components: (a) education and training, (b) hours of service, (c) sound scheduling

practices, (d) effective countermeasures, (e) incorporation of appropriate design and technologies, and (f) research."

The quote mentions general fatigue awareness as a probable countermeasure. However, even given its merits, this approach will not completely solve the problem.

Another research area revolves around determining contributing factors *leading* to pilot fatigue. Elements such as sleepiness, time since last sleep, and quality of sleep have been extensively researched. One product of these fatigue studies was the QinetiQ Alertness Model[6]. The study consisted of having 30 subjects participate in an isolated laboratory sleep and work study. Participants were given specific work and sleep schedules to adhere to while avoiding any possibility of encountering sleep deprivation. The schedule consisted of work periods of six, 12, and 18 hours which were balanced for time of day[6]. During the work cycle, alertness assessments were made every two hours[6]. The results of the experiment were twofold. Conclusions were made on alertness levels based on (1) how long it had been since last sleep, and (2) what time of day the participant woke up. According to the model (Figure 2.1), the dark red area correlates to a 'tired' individual, and the dark green portion correlates to a 'rested' individual. The study suggests that when the participants wake up around 15:00 and have been awake for nearly three hours they will be at their peak alertness. The least level of alertness was determined to be when the individual awoke around 15:00 and had been awake for nearly 16 hours. The alertness model was used as part of this research effort in scheduling when the test pilots would perform their 'rested' and 'tired' flights.

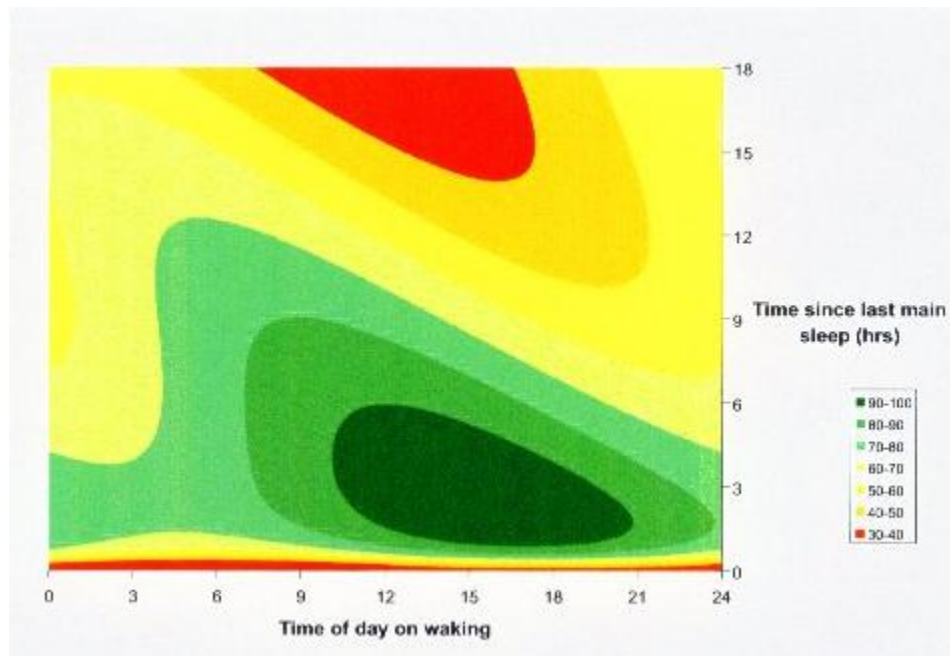**Figure 2.1**: Graphical Representation of the CHS Alertness Model[6]

Other tools have been developed based on these types of studies such as the Fatigue Avoidance Scheduling Tool[7] (FAST) which makes fatigue predictions that assist operator scheduling. The FAST tool is based on the Sleep, Activity, Fatigue and Task Effectiveness[7] (SAFTE) model, developed by Dr. Steven Hursh of Johns Hopkins

University, which uses duration and quality of sleep as metrics to predict cognitive performance effectiveness. The model can also account for variables such as balance between sleep and wakefulness, sleep inertia, and circadian rhythms. This model has been under development for more than a decade and now Dr. Hursh is under contract to the Warfighter Fatigue Countermeasures R&D Group and NTI, Inc. to modify and expand the model[8].

Other research has attempted to mathematically model the human operator. According to McRuer and Krendal the greatest amount of information exists for the single-loop case when the pilot is giving his full attention to one control task. They have shown that because many problems involve one dominant axis, this single loop configuration has been a highly productive modeling approach. This particular model is known as the crossover model[9]. Other more complicated models include the algorithmic optimal control model[10,11] and the isomorphic pilot model[12]. These models are used for more complex tasks where multiple inputs are considered and therefore a single loop configuration cannot account for the extra inputs accurately.

Mathematical models could be useful in the context of fatigue detection because they provide information on how fatigue may affect performance and suggest parameters that can be determined from input/output measurements using parameter identification techniques[13]. One such parameter would be pilot delay. It is expected that in the presence of fatigue the pilot's response time would increase causing this delay parameter to be larger in magnitude. A second parameter that could be extracted from these models as a potential fatigue indicator is response time bandwidth of the pilot and aircraft system. A larger bandwidth could indicate that the pilot is able to respond to higher frequency inputs which would be characteristic of a 'rested' pilot. Conversely, a smaller bandwidth would indicate the inability of the pilot to respond to high frequency inputs, which would be characteristic of a 'tired' pilot.

Monitoring physiological variables such as electrical activity in the brain, pulse rate, and body temperature in association with fatigue has also been investigated. In one study held by NASA's Ames Research Center the scientists used an Oxford Medilog 9200 recorder to obtain data when pilots were asleep and while awake in an attempt to get a better understanding of what 'tired' looked like through physiological readings. Another recent study went a step further to incorporate a vigilance performance measure that used reaction time to assess sustained attention. This psychomotor vigilance task (PVT)[14] is a ten minute reaction test that probes central nervous system capability. It has proved to be sensitive to the effects of sleep loss and circadian disruption[14] which could imply the onset of fatigue. One disadvantage of this monitoring approach is that its implementation would require constant contact with the pilot which could potentially cause harmful interference with the pilot's ability to carry out simple tasks or with other systems such as the action of the G-suit. Secondly, the measuring equipment would add unnecessary weight to the aircraft, which could increase fuel consumption. A third downfall of these potentially bulky systems is that in most aircraft there just is not enough room in the cockpit for any extra instruments. In addition, these studies concluded that results had high variability among pilots[15].

As we can see from these studies there has been a significant interest in pilot fatigue detection and prevention. Even though methods such as 'planned cockpit rest periods' may have the potential to reduce the amount of fatigue-related accidents, there is

no onboard system to monitor the pilot's actual condition. Mathematical models can be good for modeling but still no further research has investigated the model's possible fatigue detecting qualities. And while physiological systems have been deemed potentially problematic, they still have been the only systems that would actually be able to give real-time analysis of the pilot.

2.2 Aircraft Controls

The purpose of this section is to provide a basic understanding of how the control system in an aircraft works.

Unlike an automobile that uses a steering wheel to rotate a set of tires for steering, control of an aircraft is achieved by producing aerodynamic moments about the three axes of the aircraft body coordinate system. The aircraft can be steered when air is deflected by the movement of control surfaces, particularly the ailerons, elevator, and rudder. The yoke controls the ailerons and the elevator while the two foot pedals control the rudder.

The ailerons are located at the ends of each wing and move opposite each other. For example, if the pilot pushes the yoke to the left the left aileron moves upward and the right aileron moves downward causing the aircraft to roll to the left. The opposite happens when yoke is pushed to the right.

The elevators are on the horizontal tail of the aircraft. When the yoke is pulled backward the elevators move upward which causes the plane to go nose up. When the yoke is pushed forward the elevators move downward and this causes the plane to go nose down. This particular movement of the plane is known as pitch.

The rudder is located on the vertical tail of the aircraft. When the pilot pushes in on the left foot pedal the right pedal moves toward the pilot causing the rudder to move to the left. When the rudder moves to the left it will cause the tail of the plane to move to the right. The opposite action happens when the right pedal is pushed forward. This will cause the tail of the plane to move left. This motion of the plane is called yaw.

As these descriptions of an aircraft control system are very basic please refer to reference 16 for a more in-depth explanation.

Chapter 3

Experimental Procedure

3.1 Instructor Pilot Interviews

Studying pilot fatigue through flight dynamics has never been attempted before which manifests one question, where to start?

For a study on pilot fatigue in which none of the researchers had any flying experience, it made sense to begin by getting the opinions of expert pilots. Lear Siegler Services Incorporated has been honored to be the U.S. Army's rotary wing flight trainer since 1989. They have trained over 20,000 Army, Air Force, and Allied students to meet their world-wide commitments as military rotary wing pilots. They serve at the U.S. Army Aviation Warfighting Center, Fort Rucker, Alabama, which is the largest helicopter flight training school in the world[17]. Most of the instructors at this school have more than 6000 hours of flight experience, and since the U.S. government trusts them to train their military pilots, their answers to specifically designed questions should add substantial backing to any piloting research.

The purpose of pilot interviews was to gain firsthand knowledge in dealing with fatigue. Every pilot interviewed had extensive experience with both rotary and fixed wing aircraft. Even though experimental data used for this research was gained from a fixed wing flight simulator, pilot fatigue related to flying rotary and fixed wing aircraft were equally considered at this point in the research process. Interview questions and responses can be found in Appendix C.

Among those interviewed was Program Manager of Lear Siegler at Fort Rucker, retired Army Colonel Charles L. Gant. Colonel Gant is a former Master Army Aviator and instructor pilot[17]. Colonel Gant has roughly 6000 rotary wing flight hours and upwards of 1800 fixed wing flight hours and has flown over 25 different types of aircraft. When asked if he perceived the aircraft to respond differently when tired Colonel Gant stated that his "fine touch control skills diminished." This loss, or reduced ability to carry out otherwise normal 'rested' piloting functions is exactly what this research will prove is detectable.

Along with skills diminishing, Ed Gruetzenmacher, another instructor pilot at Fort Rucker who has over 7000 total flight hours spread over roughly 25 different aircraft, added that when fatigued his "response time was slower." Slower reaction time is a symptom of fatigue that can lead to accidents, especially in landing approaches when the pilot must be fully alert.

In response to a question asking about having to work the controls more when tired to achieve the same aircraft performance Mr. Gruetzenmacher stated that when he was "not as alert, the airplane seemed to wander" off course. This answer again supports the main hypothesis and assumptions that this research effort is based on. The aircraft wandering off course should show up on elevation sensors as well as adding detectable variance of other state variables such as sideslip angle and roll attitude angle.

In addition to obtaining information about flight conditions when fatigued, other questions were asked in order to learn about other potential sources of fatigue for future studies. One question that was asked of all pilots from Fort Rucker was, "What environmental conditions such as the sun, wind, rain, clouds, night flight, etc. hasten your

fatigue?" Every pilot agreed that some if not all of these factors took a toll on them during flight. Dale Kiel, a former army pilot with over 14,000 flight hours, commented that "flying in the clouds with turbulence" put the most strain on his ability to control his aircraft efficiently. Though flying through clouds was not included in this study, turbulence was definitely part of the flight scenario that every test pilot used for this study had to deal with. Mr. Kiel also added to Colonel Gant's comment concerning reduced ability to control the aircraft. Mr. Kiel said that when flying in a 'tired' condition he noticed that his response time deteriorated. Future studies using the delay variable found in the human operator models mentioned in the background would be supported by the testimonies of Mr. Kiel and Colonel Gant.

Interviewing the flight instructors from Fort Rucker provided significant support confirming both the utility of this research effort and the assumptions it was based on. The interviews validated that the aircraft should show signs of dynamic change in the presence of a fatigued pilot. Words such as the 'loss of fine touch skills' had the conclusion that the pilot would have to provide more compensation to keep the aircraft on course. Remarks such as this also provided a positive outlook in finding that there should indeed be an increase in standard deviation and mean of the tracking errors of the state and control variables, which is what the detection schemes would be monitoring in order to classify either a 'rested' or 'tired' pilot condition. The statements mentioning boredom causing fatigue on long flights led to the belief that fatigue detection would be very successful for the steady level flights. In addition to solidifying hypotheses made in the beginning stages of research, the interviews gave vital support for other areas of research related to fatigue detection discussed in the background section such as the possible fatigue detecting variables within the mathematical models.

3.2 Flight Simulator

The WVU College of Engineering and Mineral Resources' Mechanical and Aerospace Department 6 degrees-of-freedom flight simulator was used for this research effort. The Motus 600 Flight Simulator[18] shown in Figure 3.1, manufactured by Fidelity Flight Simulation offers a realistic flight environment allowing "true" motion cues flight simulation capabilities using electric actuators. A 140° four-monitor, wrap-a-round external visual display provides high quality visual cues.

The Laminar Research X-Plane[19] flight simulation software is used to drive the simulator system. X-plane[19] is a commercial comprehensive aircraft simulation package featuring high capabilities and flexibility in selecting the simulation scenario. The software saves the data during the simulation so that selected parameters can be analyzed later. Also, the software has the ability to simulate still air conditions as well as varying levels of turbulence. The cockpit accommodates dual controls and instrument clusters. Visual information in the cockpit is provided by a total of 6 LCD visual displays which can be seen in Figure 3.2. Two displays host the instrument clusters and the other four provide external visual cues. Flight scenario set-ups/changes and monitoring the simulation are preformed from the operating station located to the right of the cabin in Figure 3.1.

Figure 3.1: WVU 6DOF Motion Base Flight Simulator - General View

Figure 3.2: WVU 6DOF Motion Base Flight Simulator - Cockpit View

3.3 Test Pilot Acquisition

The next step in the experimental phase was finding pilots for the study. Five WVU Aerospace Engineering students with flying experience volunteered for the project. Among the five pilots, three of them were considered experimental and the other two were used for validation purposes only. The data collected from the experimental pilots was thoroughly examined and used for analysis. The validation data from the other two pilots was only used at the end of the project to verify the designed detection schemes. As results will show, the scheme shows definite implementation potential.

3.4 Test Pilot Classification ~ Rested/Tired

The CHS Alertness Model[6] from Chapter 2 Figure 2.1 was utilized for the purpose of ensuring either a 'rested' or 'tired' pilot condition. Based on the model, the students were given specific instructions on when to wake up depending on which test they were flying that particular day. The times of the tests were scheduled based on actual waking time and time since last sleep to guarantee that the pilots were verified as 'rested' or 'tired' according to the Alertness Model[6].

Each pilot was given a post flight questionnaire, which consisted of ten questions that were designed to gain additional information regarding the pilots' condition and performance (see Appendix B). Questions one and two let the researchers know when each pilot woke up and roughly how long each one slept. Questions two and three centered on the quality of sleep and how rested the pilot felt upon waking. Questions five and six gained information regarding any substances that could have altered the pilots flying ability such as any medications taken as well as roughly how much caffeine was consumed prior to simulation. Questions seven through ten were designed to allow each pilot to comment on their performance.

3.5 Flight Scenario

A flight scenario was developed for the simulation that incorporated different types of maneuvers. Each pilot flew the scenario while 'rested' and then again when 'tired'. The test pilots were given a chance to study the scenario and take two practice flights before any data collection took place. The following was the complete flight scenario flown by each pilot. The average duration of each simulation was approximately 40 minutes.

1. Take-off.
2. Climb up to 1000 ft AGL at 110 knots.
3. Steady climb up to 3700 ft AGL at 140 knots.
4. Maintain steady state level symmetrical uniform flight for 1 minute at 3700 ft and 140 knots.
5. Perform a coordinated turn, full circle to the left, at 45° and 140 knots.
6. Maintain steady state level symmetrical uniform flight for 30 seconds.
7. Accelerate up to 160 knots in 3 minutes.
8. Decelerate back to 140 knots in 3 minutes.
9. Maintain steady state level symmetrical uniform flight for 30 seconds.
10. Decelerate to 90 knots (use landing gear and flaps).
11. Perform left coordinated turn, full circle at 5°.

12. Maintain steady state level symmetrical uniform flight at 90 knots with maximum turbulence for 4 minutes.
13. Perform a coordinated turn to the left with turbulence at 5° for a full circle.
14. Perform a coordinated turn to the right with turbulence at 5° for a half circle.
15. No turbulence, accelerate back to 140 knots.
16. Maintain steady state level symmetrical uniform flight for 30 seconds at 140 knots.
17. Perform a pitch attitude doublet (+10° and −5°) while maintaining altitude, velocity, and heading.
18. Maintain steady state level symmetrical uniform flight for 30 seconds at 140 knots.
19. Perform a roll attitude doublet (±60°) while maintaining altitude, velocity, and heading.
20. Maintain steady state level symmetrical uniform flight at 140 knots with maximum turbulence for 6 minutes.
21. Cancel turbulence, prepare for landing.
22. Follow the same standard procedure to land.

There were 10 of the total 22 steps in the flight scenario identified as maneuvers for this investigation. Each maneuver was given its own number that will be referenced from here on. However the following table identifies the step number within the scenario and defines the corresponding maneuver and new maneuver number.

Table 3.1: List of Maneuvers Chosen from Flight Scenario for Fatigue Study

Scenario Step #	Maneuver	New #
6	Steady Level Flight	1
5	Coordinated Turn at 45deg	2
11	Coordinated Turn at 5deg	3
12	Steady Level Flight w/Turb.	4
13	Coordinated Turn 5deg L w/Turb	5
14	Half Coordinated Turn 5deg R w/Turb	6
19	Roll Doublet	7
16	Steady Level Flight	8
20	Steady Level Flight w/Turb.	9
17	Pitch Doublet	10

During a steady level flight the pilot was to keep the aircraft level, on heading, and at the specified speed and altitude. The coordinated turns required the pilot to perform either a full or half circle turn while keeping a preset bank angle, velocity, and altitude constant throughout the maneuver. For the roll doublet, starting at steady level flight, the pilot first rolled the aircraft 60° to the left, then back through zero to 60° to the right, and ended the maneuver by returning to steady level flight. For the pitch doublet, starting at steady level flight, the pilot pulled the nose of the aircraft up 10°, then back through zero down to -5°, and ended by returning to steady level flight.

3.6 State and Control Variables

As part of the data acquisition process, Laminar Research X-Plane[19] Flight Simulation software was used to record time histories of variables during each flight.

Sampling rate = 10Hz

The *state variables* recorded were:

velocity (V)
angle of attack (α-alpha)
side-slip angle (β-beta)
roll, pitch, and yaw rates (p, q, and r)
roll, pitch and yaw attitude angles (φ-phi, θ-theta, and ψ-psi)

The *control variables* recorded were:

elevator deflection (δ_e)
aileron deflection (δ_a)
rudder deflection (δ_r)

3.7 Data Processing

The time histories of each variable were recorded in matrix form in a .out file. Each column within the matrix corresponded to a different parameter. Due to the 40 minute test duration the size of the file from the simulation software was extremely large. This file could be opened in Microsoft Word® but numerous undesirable format characters were spread throughout the file and had to be eliminated before the data could be transferred to Matlab® and used for analysis. Because the raw data files were so large, they had to be divided into 10-15 smaller files in order to remove all of these characters in a timely fashion. Once these unwanted characters were removed, the data from the 10-15 separate files was saved as a Matlab® data file. With the data formatted, the next step was to pick out the individual maneuvers for each pilot's simulation.

3.8 Maneuver Identification

In order to determine the specific maneuver intervals Matlab® was used to plot five state variables for the entire duration of the simulation. Only example plots will be included as the process was the same for each pilot and because the graphs looked so much alike for each specific maneuver. The variables plotted were velocity, roll, pitch, and yaw attitude angles (φ, θ, and ψ), and angle of attack (α). Figure 3.3 is an example of how the entire simulation would appear.
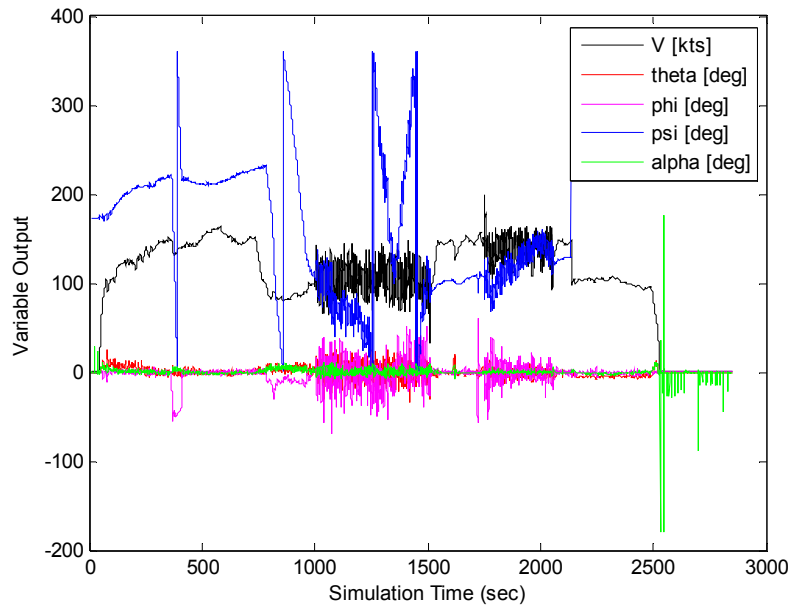
Figure 3.3: Entire Flight Scenario as Performed by Pilot #4

Using the flight scenario outline in conjunction with the outputs from the selected variables each maneuver can be identified. The first maneuvers identified were the coordinated turns as they were the easiest to detect using roll angle(φ) and yaw angle(ψ). For example, the way to identify maneuver number five, a coordinated turn with a 45° banking angle, is to look for when yaw angle goes through a complete 360° cycle and when roll angle goes to negative 45°. This happens at roughly 400 seconds into the simulation. The other turns were identified using this same procedure. When identified and isolated, the maneuver will appear as displayed in Figure 3.4.
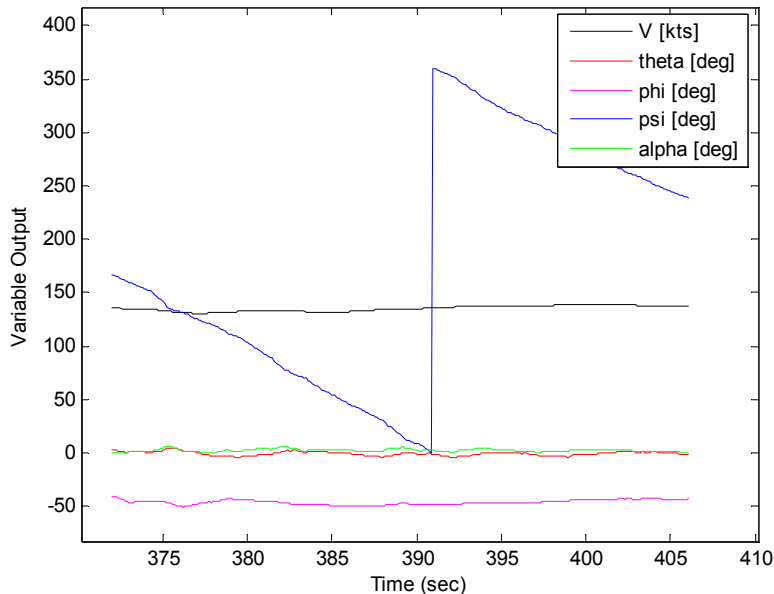

Figure 3.4: Pilot #4 Maneuver 2 – Pre-Processed Data to be Used for Analysis

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In order to use the data for analysis, yaw angle had to undergo additional processing to get rid of the jump from zero to 360 degrees. The jump is a consequence of how the flight simulator measures the yaw angle value internally. It measures values of yaw attitude angle from 0 to 360 degrees only. A simple 'for' loop was used within Matlab® to shift the second half of the data downward so that yaw angle ranged from roughly 180° to -180°, which made the analysis much easier. At no time during the filtering was the integrity of the raw data compromised. Figure 3.5 is characteristic of what the usable data for the coordinated turn will look like.
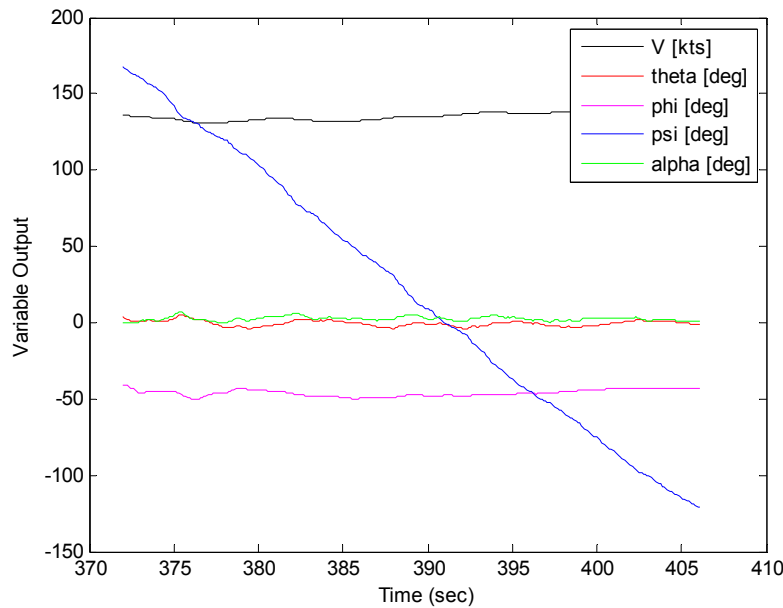

Figure 3.5: Pilot #4, Maneuver 2 – Processed Data Used for Analysis

The next maneuvers identified were the doublets. A doublet is simply defined as back and forth rocking of the aircraft. A roll doublet means that while maintaining heading and speed the plane will roll to one side and then other ending up back at level flight. A pitch doublet means the aircraft will go nose up, then nose down and again return back to level flight. In these maneuvers the pitch and roll attitude angles were used for identification. For the pitch doublet, pitch angle goes from zero to +10° to -5° and then back to zero. The roll doublet called for roll angle to go from zero to $^+/$-60 to $^-/_+$60 and then back to zero. Unlike the pitch doublet, for the roll doublet the pilot was not ordered to go either left or right first as it did not matter for this study. However, as the 'rested' case was considered the reference, pilots were ordered to repeat the same first direction during their 'tired' simulation. Figures 3.6 and 3.7 show both the pitch and roll attitude doublets respectively.
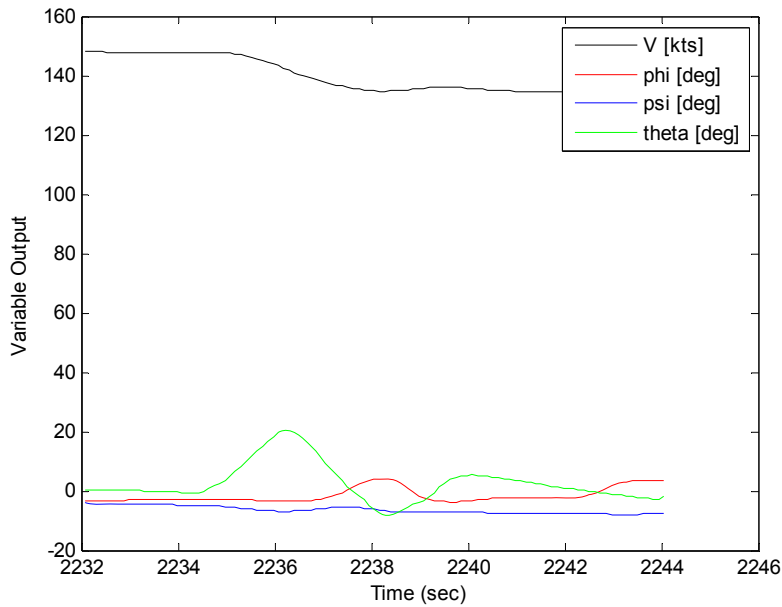
Figure 3.6: Pilot #2 Maneuver 10 – Characteristic Raw Data
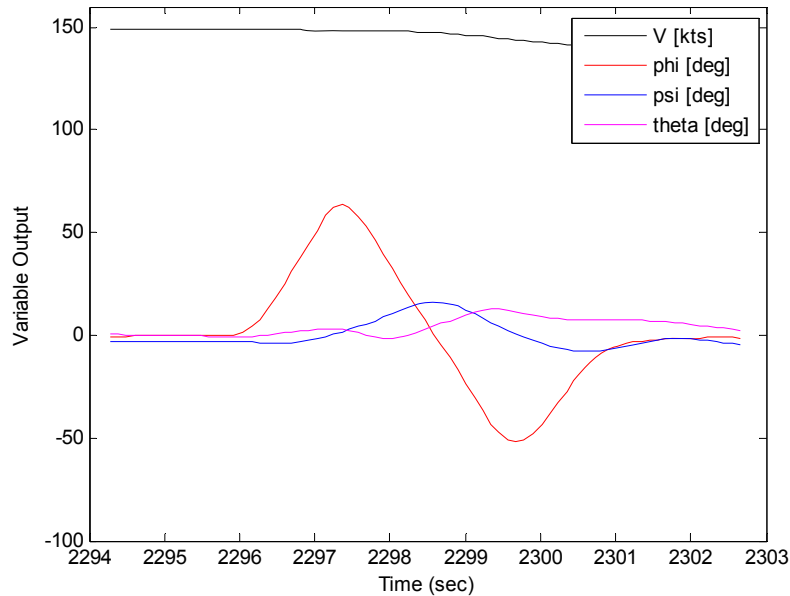
Figure 3.7: Pilot #2 Maneuver 7 – Characteristic Raw Data

The next type of maneuver to identify was steady level flights. During these maneuvers the pilot was instructed to keep velocity, altitude, heading, etc. constant. Most steady flights were used to break up the sequence of other maneuvers. Therefore, once the other maneuvers were identified, the steady level flights became the data occurring between most maneuvers. For example, each pilot was to perform the pitch doublet then go into a steady level flight for 30 seconds before continuing with the roll doublet. Knowing that the steady level flight occurred between these two maneuvers and having

already located the doublets, the steady level flight condition could be properly identified. A characteristic steady level flight condition can be observed in Figure 3.8. There were two other steady level flight conditions, but they were executed during simulated turbulence.
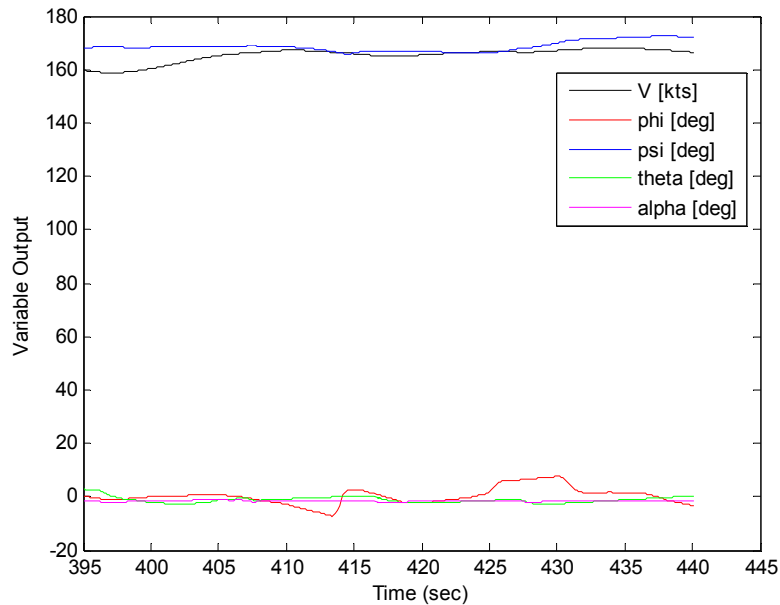
Figure 3.8: Pilot #3 Maneuver 1 – Characteristic Raw Data

The simulator can produce flight conditions that mimic realistic interferences that a pilot flying an actual aircraft could encounter, one of which is turbulence. There is a mechanism within the X-Plane[19] software that allows the user to set the amount of turbulence the pilot will encounter. For the purposes of this study maximum turbulence was selected for all maneuvers in hopes that the more severe the turbulence the easier it would be to see greater variances between the 'rested' and 'tired' state variables.

Turbulence was simulated for both coordinated turns and steady level flights. The methods for finding these two types of maneuvers without turbulence were used again when identifying them in presence of turbulence. Looking back on Figure 3.3 there are noticeable areas of data that appear chaotic as compared to rest of the data. These chaotic areas were due to the introduction of turbulence. Figures 3.9 and 3.10 represent characteristic plots of both a steady level flight and a coordinated turn in turbulence.
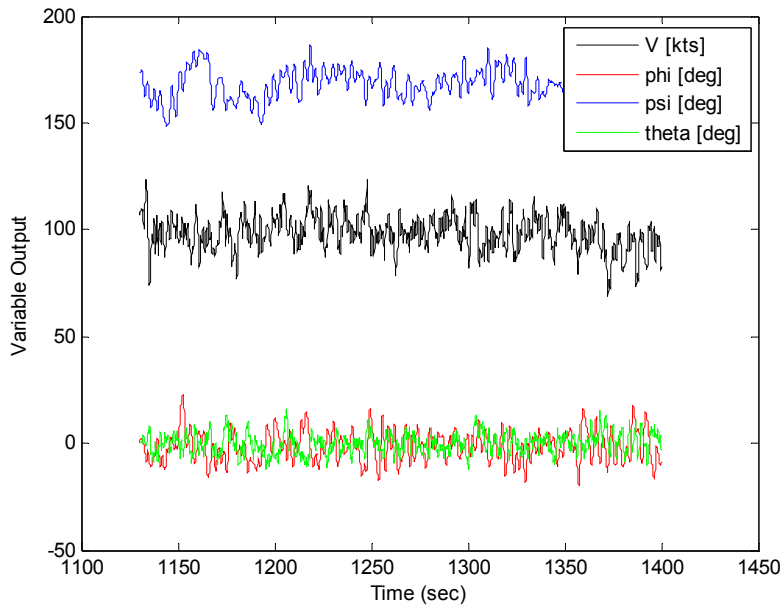
Figure 3.9: Pilot #1 Maneuver 4 − Characteristic Raw Data
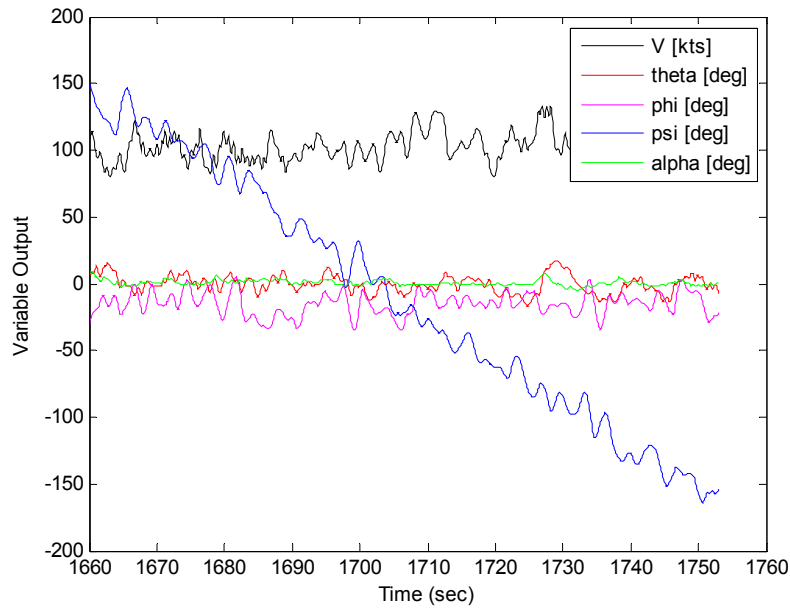
Figure 3.10: Pilot #4 Maneuver 5 − Filtered Data Used for Analysis

      The maneuver identification process was the last step leading up to analyzing each state and control variable for their fatigue detecting capabilities. As stated, the plots and specific maneuvers discussed in this section are examples of the corresponding maneuvers.

3.9 Analysis Tools

This research effort required constant use of Matlab® programs to load data sets for each pilot and maneuver for analysis. Graphical User Interfaces (GUIs) were created to make this process quick and consistent. Figure 3.11 displays the first GUI created. The GUI allowed the user to select maneuver type, pilot, and which metrics were to be calculated (see section 4.1). A second GUI, in Figure 3.12, was created for the composite variable analysis and implementation of the detection schemes.
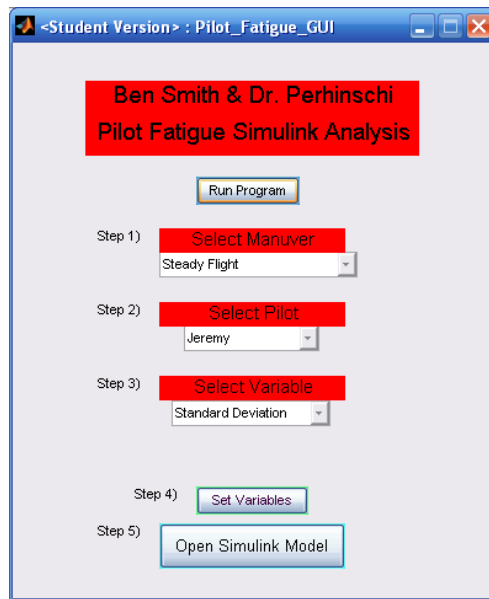
Figure 3.11: GUI Used for the Calculations of Standard Deviation and Mean of the State and Control Variable Tracking Errors

Figure 3.12: GUI Used for Composite Parameter Analysis and Detection Scheme Implementation

Chapter 4

Methodology

4.1 State and Control Variable Analysis

This research effort was based on the assumption that the performance of a 'tired' pilot is lower than the performance of a 'rested' pilot, and that the lowered performance can be detected through state and control variables.

It was also expected that the lowered performance of the 'tired' pilot would vary among different types of maneuvers. For example, the pilot may have the most difficulty keeping heading constant during a steady level flight, b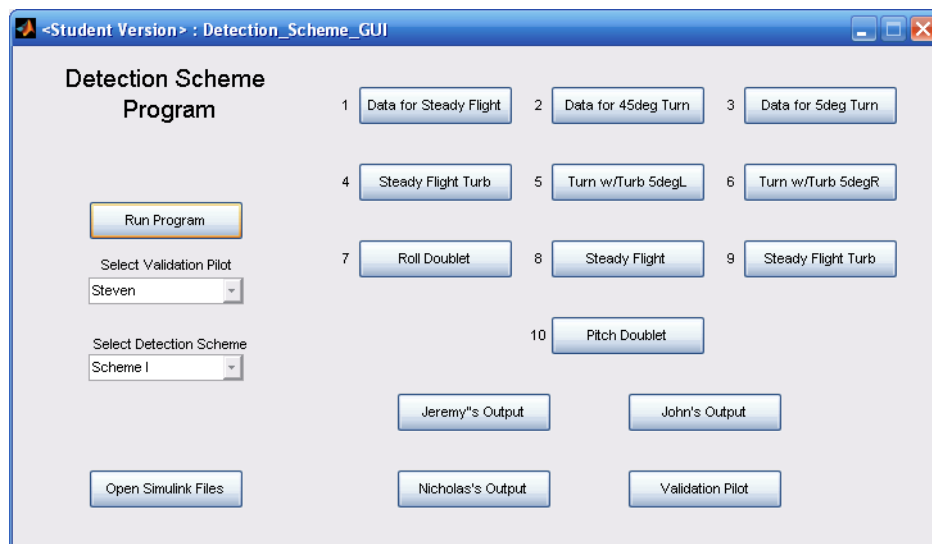ut have more difficulty keeping bank angle constant during a coordinated turn. Heading and bank angle involve two different state variables which means that the lowered performance of these two maneuvers would be characterized by two different states. Reasons illustrated by this example are why the variables (listed in Chapter 3) were selected for pilot performance evaluation.

The method of quantifying the difference in performance of a 'rested' and 'tired' pilot started with tracking errors. Tracking error was defined as the distance between the 'actual' variable value and the target value (Eq. 4.1). Absolute value was used because whether the tracking error was positive or negative was not of concern for this investigation, only the magnitude of the error.

$$\text{Tracking Error} = |(\text{actual}) - (\text{target})| \qquad\qquad 4.1$$

The target values for most of the variables were defined in the flight scenario in Chapter 3. The ones that were not defined had to be created based upon what the pilot was trying to achieve.

The next step was to evaluate the tracking errors. Standard deviation and mean were the two metrics used. Standard deviation is the most common measure of dispersion or variance for a set of data[20]. This will capture the increases in variability of the tracking error data as a product of the pilot's decreased performance level. The mean of the tracking error was also calculated. The mean was also believed to increase as the pilot became 'tired' which would cause an increase in overall magnitudes of the tracking errors. The Candidate Detectors section of this chapter will describe how the mean and standard deviation were analyzed.

4.2 Target Values

The target values that the pilots tried to achieve differed somewhat between maneuvers. First to be defined were the targets for the steady state maneuvers. Depending on what was dictated in the flight scenario, the target was valued as such. For each of the state and control variables mentioned in the Chapter 3 an array of tracking error values was generated for the length of the maneuver. Then the standard deviation and mean were calculated for the entire tracking error vector.

Targets for the coordinated turns were basically the same with the exception of the roll and yaw attitude angles. The roll attitude angle target was defined according to the banking angle specified in the flight scenario. The yaw attitude angle target value had to be created. Figures 4.1 and 4.2 display a typical coordinated turn.
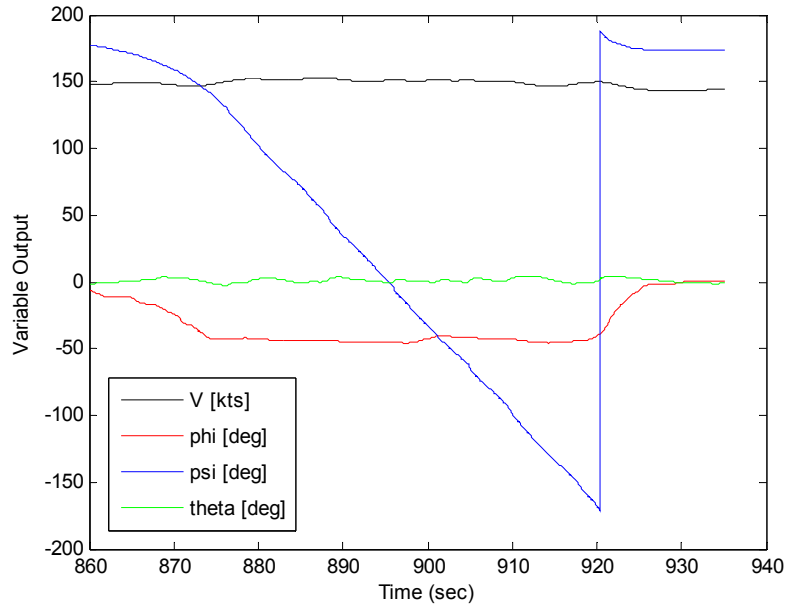
Figure 4.1: Pilot #2 Maneuver 2 – Coordinated Turn with 45 Degree Bank Angle
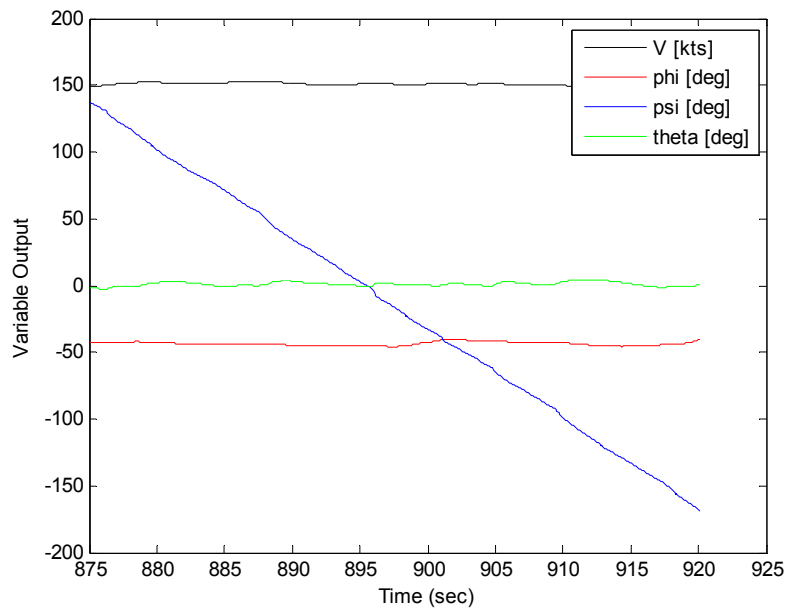
Figure 4.2: Pilot #2 Maneuver 2 – Characteristic Data Used for Analysis

The maneuver start time was defined as the point when the pilot reached the desired banking angle, which was 45° in this case. The end time was defined as the point when the banking angle started to returned to zero. The reasoning behind this selection was due to the fact that the pilot needed to hold the banking angle constant for the duration of the maneuver. The two transient regions at the beginning and end of the

maneuver were not 'steady state' and therefore were not of interest for analysis. When the actual start and end times were used the plot would appear as in Figure 4.2.

Only after the maneuver had been completely defined could the yaw angle target be created. The target was developed on the premise that the pilot was trying to make a perfect circle turn. If the turn was a perfect circle, yaw angle would be a perfectly straight line in Figure 4.2. Therefore, a straight line was created between the first and last data points. The tracking error then became the actual yaw angle value minus the corresponding value from the target. This procedure was repeated for all other coordinated turns throughout the flight scenario in both 'rested' and 'tired' cases. Figure 4.3 displays a close up view of both the actual yaw angle values and the target values generated.
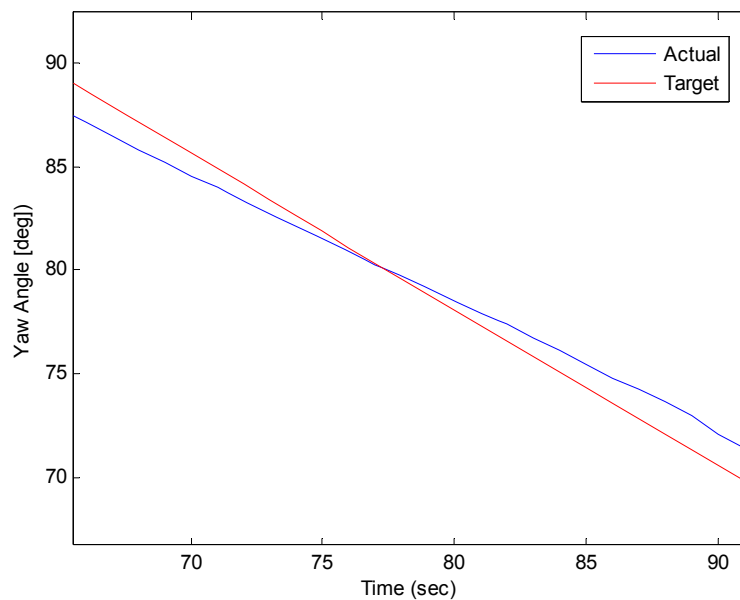
Figure 4.3: Pilot#2 Maneuver 2 – Actual Yaw Attitude Angle Compared to Target Value

The target value for the 'rested' case was considered to be characteristic of a turn the pilot would always try to achieve, which is why the 'tired' yaw angle value for the same turn was compared to the target values obtained from the 'rested' data.

The other types of maneuvers were the pitch and roll doublets. The roll doublet had both steady state targets, such as velocity, and a non-steady target, such as roll angle. The target values for roll angle had to be created.

Figure 4.4 shows the roll angle going through the proper range described by the flight scenario. Start and end time for the doublets needed to be determined just as with the coordinated turns. It was decided that the starting point should be when the pilot begins to move the yoke to start the roll. The variable in Figure 4.4 noted ail_y is the pilot's input through movement of the yoke controlling the ailerons. Figure 4.5 shows a close up of the ail_y output.
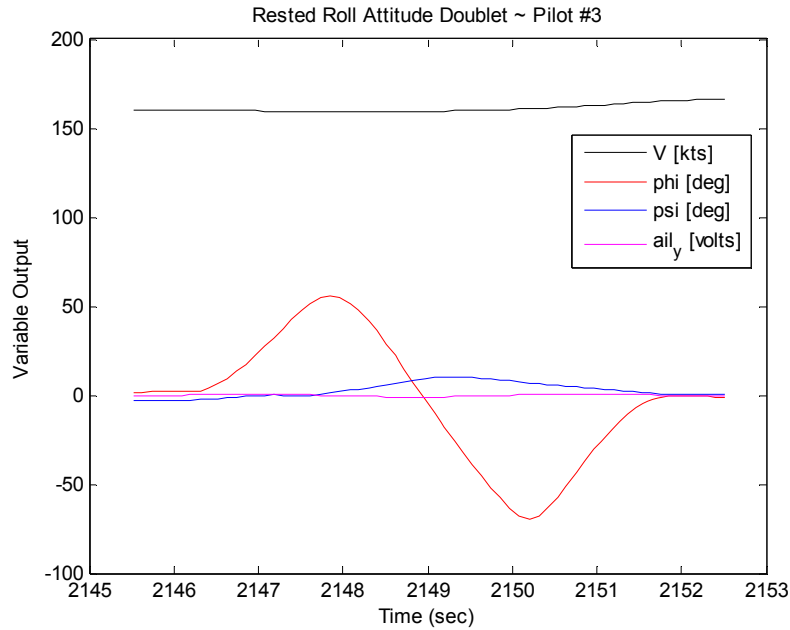
Figure 4.4: Pilot #3 Maneuver 7 − Characteristic State Variable Values for Roll Doublet
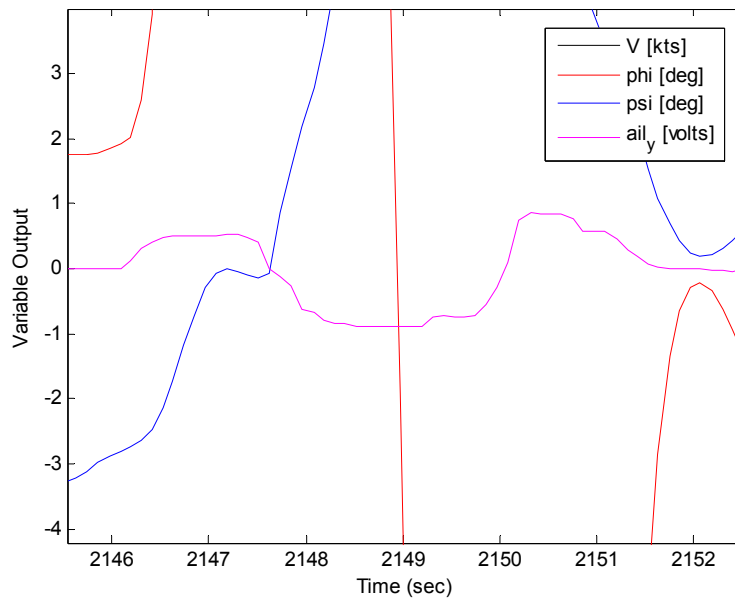
Figure 4.5: Pilot #3 Maneuver 7 − Yoke (ail$_y$) Input from Pilot During the Roll Doublet

Figure 4.5 shows when the pilot begins moving the yoke which is where the maneuver started. The next step was to develop the target values for the roll angle throughout the maneuver.

It was assumed that the doublet performed by a 'rested' pilot would be the best of his ability. Therefore, this execution is what the pilot would try to achieve every time. The exact values of the 'rested' data were not defined as the target values. Figure 4.6 shows target values for the roll doublet.
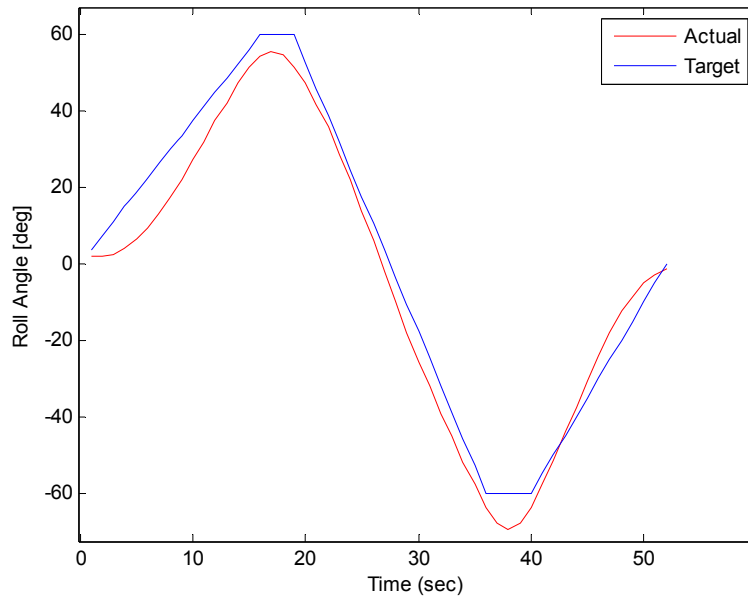
Figure 4.6: Pilot #3 Maneuver 7 – Characteristic Target Values for the Roll Doublet

In Figure 4.6 the target values follow what was considered the 'perfect' maneuver based on how the pilot performed. The first step was to find the peaks in the actual roll angle value. Depending on the duration of the peaks of the actual data a corresponding duration was assigned to the target with values of either ±60° at the specific times within the maneuver. Then using the start point of the maneuver linear values were filled in for the data points until the +60° values were reached. This process was repeated for target values between +60° and -60°, and also for the target values from -60° until the end of the maneuver. Even though each pilot was trying to do the same maneuver, it was believed that the best results could be achieved if target values were determined using each of the pilots' 'rested' values.

The target values for the pitch doublet were found in the same manner as for the roll doublet. The only difference with the pitch doublet was that target values for pitch angle were generated instead of values for roll angle.

4.3 'Off-line' Fatigue Detectors

Once the mean and standard deviation were calculated for both 'rested' and 'tired' tracking error data sets for each pilot, the values were organized into a spreadsheet to determine which variables would be good fatigue detectors. The state variables that showed an increase in both mean and standard deviation of the tracking error were considered to be good fatigue detectors. The variables that showed an increase in only one or other were noted, but were considered mediocre fatigue detectors. The variables that did not show an increase in either the standard deviation or the mean were not included in the list of possible fatigue detectors.

First, the state and control variables were analyzed individually for each pilot and maneuver to see which variables followed the 'increasing' trend the most often. Table 4.1 is an example of how the variables were organized for each maneuver.

Table 4.1: Standard Deviation and Mean Values of State Variable Tracking Errors

Maneuver #3 Coordinated Turn @ 5deg				
Pilot #1				
	Mean		Standard Deviation	
	Rested	Tired	Rested	Tired
V (knots)	11.0184	8.9982	2.5619	4.237
α (deg)	-0.6641	-0.1485	0.6668	1.294
β (deg)	-0.2077	2.1635	0.42	0.4858
p (rad/s)	-0.1039	0.0827	0.5696	2.2416
q (rad/s)	0.6714	1.6487	1.3199	2.4076
r (rad/s)	-2.4715	-3.8253	0.6794	1.2348
θ (deg)	-0.4799	0.5703	1.7777	4.3284
φ (deg)	-8.3799	-16.4799	3.7204	5.9683
ψ (deg)	13.1394	-1.3196	7.7322	6.2614
ail_y	0.0347	0.0398	0.013	0.0546
rud_y	-0.0438	0.1022	0.0236	0.0172
$elev_y$	0.1605	0.1825	0.0544	0.0691
Pilot #2				
	Mean		Standard Deviation	
	Rested	Tired	Rested	Tired
V (knots)	5.6232	13.6575	1.6489	2.0687
α (deg)	0.1773	1.0363	0.187	0.6294
β (deg)	1.1391	1.4714	0.3458	0.5429
p (rad/s)	0.0077	0.0514	1.0031	1.4564
q (rad/s)	0.428	0.723	0.3665	0.9653
r (rad/s)	-2.1169	-2.4965	0.6163	0.8714
θ (deg)	0.4106	1.1151	1.2554	1.493
φ (deg)	-6.2112	-9.3263	2.7864	4.5896
ψ (deg)	1.6436	-18.498	5.1536	11.9493
ail_y	0.0528	0.0239	0.0245	0.0321
rud_y	0.0643	0.0853	0.0168	0.0305
$elev_y$	0.1961	0.1618	0.0129	0.0251
Pilot #3				
	Mean		Standard Deviation	
	Rested	Tired	Rested	Tired
V (knots)	11.9878	13.4791	3.5219	5.5097
α (deg)	-1.0685	-1.1837	0.9485	1.2548
β (deg)	0.6144	-0.023	0.3375	0.3853
p (rad/s)	-0.0325	-0.0505	0.9205	1.5658
q (rad/s)	0.4292	0.5794	2.1224	2.3196
r (rad/s)	-2.0988	-2.4003	0.4816	0.5444
θ (deg)	-0.9897	-1.1921	2.4928	4.098
φ (deg)	-6.726	-8.2319	1.5152	2.0409
ψ (deg)	-3.4063	-1.751	4.1693	2.2659
ail_y	0.0308	0.0343	0.0212	0.037
rud_y	0.0148	-0.0297	0.0171	0.0166
$elev_y$	0.1389	0.1379	0.0749	0.0795

After the values of the mean and the standard deviation were completed for all maneuvers and pilots, tests were done to find which state variables should be used for fatigue detection. The variables that followed the increasing trend for at least 50% of the time were selected.

The first test involved looking at each state variable from all three pilots for the turning maneuvers. Table 4.2 below shows the results of this test.

Table 4.2: Success Percentage of Each State Variable for the Experimental Pilots' Turning Maneuvers

Out of 4 Maneuvers	Turns all Pilots (3)	
	Number	% correct
V	6	50%
α	11	92%
β	5	42%
p	5	42%
q	6	50%
r	4	33%
θ	8	67%
φ	9	75%
ψ	5	42%
ail_y	6	50%
rud_y	7	58%
$elev_y$	5	42%

The number column is the count of how many times the variable followed the trend out of the total. The total would be 12 since there are 4 turning maneuvers for each of the three experimental pilots. The conclusion of the test was that velocity, angle of attack (α), pitch rate (q), pitch angle (θ), roll angle (φ); and aileron and rudder input are promising and should be used for detecting pilot fatigued during a turn.

The next test was basically the same but for the steady level flight conditions. Table 4.3 shows the results of this test.

Table 4.3: Success Percentage of Each State Variable for the Experimental Pilots' Steady Level Flight Maneuvers

Out of 4 Maneuvers	Steady Flight all Pilots (3)	
	Number	% correct
V	5	42%
α	8	67%
β	7	58%
p	6	50%
q	4	33%
r	7	58%
θ	7	58%
φ	8	67%
ψ	7	58%
ail_y	5	42%
rud_y	7	58%
$elev_y$	1	8%

The results showed that when trying to detect fatigue during a steady level flight condition angle of attack (α), side-slip angle (β), yaw rate (r), pitch angle (θ), roll angle (φ), yaw angle (ψ), and rudder input should be monitored.

The third test was for the doublet maneuvers. The results from this test showed that velocity, angle of attack (α), pitch rate (q), pitch angle (θ), roll angle (φ), yaw angle (ψ), aileron input, and elevator input should be considered when detecting fatigue for a doublet maneuver.

Table 4.4: Success Percentage of Each State Variable for the Experimental Pilots' Doublet Maneuvers

Out of 2 Maneuvers	Doublets all Pilots (3)	
	Number	% correct
V	5	83%
α	3	50%
β	1	17%
p	2	33%
q	3	50%
r	2	33%
θ	5	83%
φ	4	67%
ψ	4	67%
ail_y	4	67%
rud_y	2	33%
$elev_y$	3	50%

The fourth test was to look at each variable for all maneuvers but now for each individual pilot. There were 10 maneuvers considered for each pilot so the number column is the how many times out of ten the particular state variable followed the increasing trend from 'rested' to 'tired'. Table 4.5 below shows the results.

Table 4.5: State Variable Success for Each Experimental Pilot

Total of 10 Maneuvers for each Pilot								
All Maneuvers Pilot #1			All Maneuvers Pilot #2			All Maneuvers Pilot #3		
Number	% correct		Number	% correct		Number	% correct	
4	40%	V	6	60%	V	6	60%	
7	70%	α	8	80%	α	7	70%	
5	50%	β	5	50%	β	3	30%	
4	40%	p	5	50%	p	4	40%	
3	30%	q	6	60%	q	4	40%	
4	40%	r	5	50%	r	4	40%	
6	60%	θ	6	60%	θ	8	80%	
8	80%	φ	7	70%	φ	6	60%	
4	40%	ψ	6	60%	ψ	6	60%	
5	50%	ail_y	5	50%	ail_y	5	50%	
4	40%	rud_y	8	80%	rud_y	3	30%	
3	30%	$elev_y$	3	30%	$elev_y$	3	30%	

The results from this test were used to observe what differences existed between pilots. For example, yaw angle (ψ) would be a good candidate for fatigue detection for pilot #3 and #2, but not for pilot #1. These issues are important to remember when trying to implement a universal fatigue detection scheme. Another interesting result of this test can be linked to the amount of flight experience the pilot had. Pilot #2 had the most flying experience, then pilot #3, and pilot #1 had the least amount of experience. As it turned out all but one variable out of the 12 would be considered good fatigue detectors for pilot #2. Pilot #3, who was next, had 6 out of 12 variables that would be good detectors. Having the least experience, pilot #1 only had 5 of the 12 variables follow the increasing trend. So to determine which variables should be considered as 'universal' fatigue detectors, each of the percentages for state variables in the table above were averaged and can be seen in the Table 4.6.

Table 4.6: Overall Averaged State Variable Success Percentages

All Maneuvers All Pilots		
States	Overall Percentage	Probable Fatigue Detectors
V	53%	x
α	73%	x
β	43%	
p	43%	
q	43%	
r	43%	
θ	67%	x
φ	70%	x
ψ	53%	x
ail_y	50%	x
rud_y	50%	x
$elev_y$	30%	

Table 4.6 was used as an overall conclusion to the four standard deviation and mean tests for probable 'universal' fatigue detectors. The conclusions from the first three tests were used to supplement the conclusions in Table 4.6.

4.4 'Online' Fatigue Detectors

In the previous section the mean and standard deviation of the tracking error were calculated for the duration of the maneuver, but the actual fatigue detection scheme will be 'online'. Any aircraft computer can easily record the same 12 state variables that were chosen for this fatigue analysis, which means that real time data points could be fed to the detection scheme. Simulink[21] is a program within Matlab® that was used to simulate this 'real time' data. Figure 4.7 shows the flow of information within Simulink.
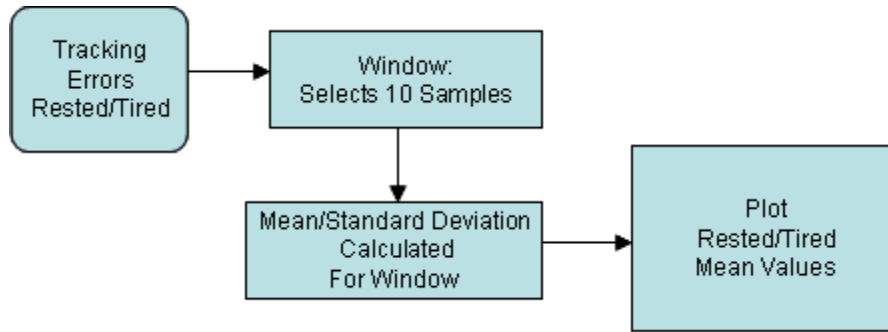
Figure 4.7: 'On-line' Calculation of Mean/Standard of Tracking Errors

The tracking errors are fed into the open loop above one at a time. In order to make a useful calculation of either the mean or standard deviation more than one data point was needed. Ten samples were used for these calculations. Imagine a window with ten slots. Each of the slots can hold one data point. Once ten samples completely fill the window mean and standard deviation are calculated for the ten data points. The data flows through the window from right to left. To illustrate exactly what is happening the following three vectors are representative of three consecutive windows of data. The numbers represent different tracking error data points.

(1 2 3 4 5 6 7 8 9 10)...next one(2 3 4 5 6 7 8 9 10 11)...and then(3 4 5 6 7 8 9 10 11 12)

The outputs of the simulation are the 'online' calculations of the standard deviation and mean for the 'rested' and 'tired' data. Figure 4.8 is the plot displaying the 'on-line' mean calculated for the tracking error of side slip angle (β). Even though this is a plot of only one of the 12 state variables used the other 11 were analyzed in the same fashion.
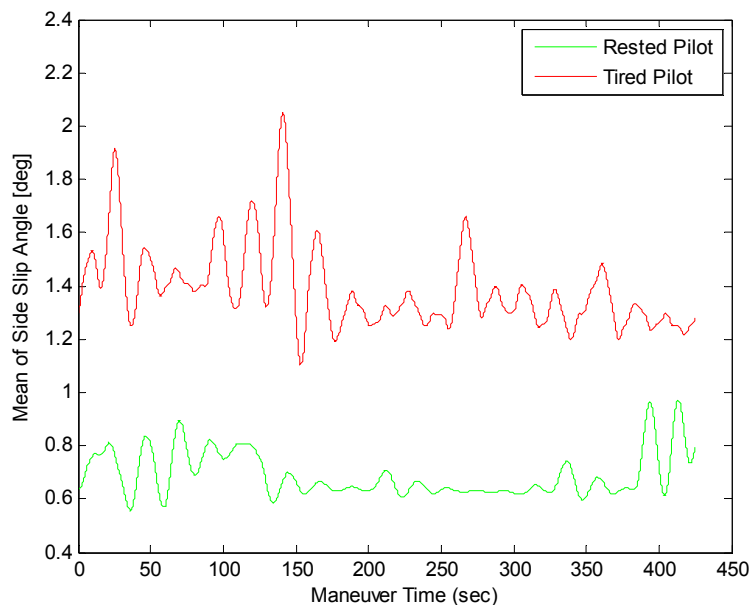

Figure 4.8: Pilot #2 Maneuver 1 – 'On-Line' Mean of Side-Slip Angle

Separation between the two sets of data with the 'tired' mean of the tracking error higher than the 'rested' mean is what was hoped for. Just as in the previous section, an increase in the mean and standard deviation of the tracking error was expected due to the pilots' deteriorated ability to control the aircraft due to fatigue. Figures 4.9 and 4.10 show the data of the other two experimental pilots for the same maneuver and state variable.

It was noticed that individual pilot variability had a significant impact on the amount of separation and the specific range of values over which the separation took place. For example, pilot #2 had the most experience and his data had the most separation for the mean of the side-slip angle as seen in Figure 4.8. Pilot #1 had the least experience and the data in Figure 4.9 shows that the rested values were higher for more than 60% of the maneuver time. Another difference between Figures 4.8 & 4.9 was the magnitude of the data sets. For pilot #2 the data ranged from roughly 0.6 to 2.0 while all of the values from pilot #1 were 1.0 or below. These issues had to be considered when determining which variables should be used as fatigue detectors.
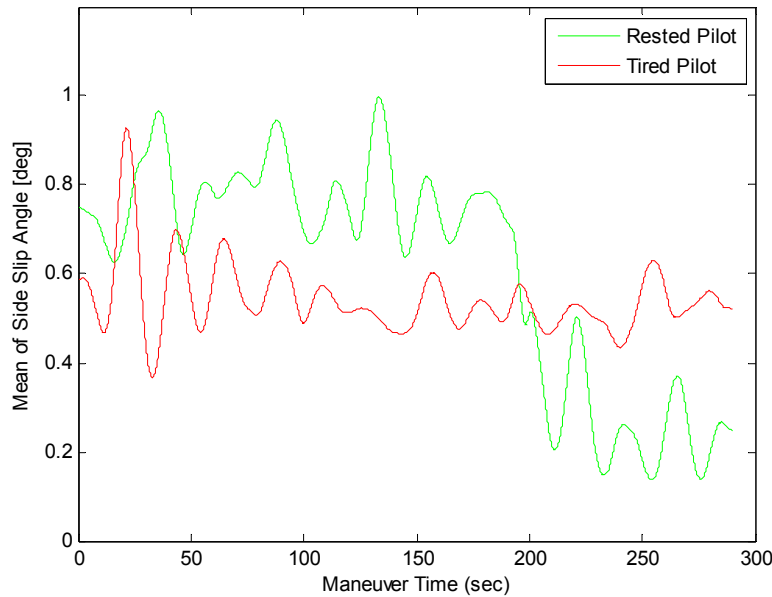

Figure 4.9: Pilot #1 Maneuver 1 – 'On-Line' Mean of Side-Slip Angle

More weight was given to the results from the most experienced pilot with regard to separation, meaning that when pilot #2's data was the only one out of the three that followed the increasing trend from 'rested' to 'tired' the variable in question would not be discarded for that particular maneuver. The different ranges of the separation from pilot to pilot were not considered when actually selecting the candidate detectors. However, these differences definitely impacted the detection schemes that will be discussed later.

Plots such as Figures 4.8-4.10 were used along with the 'off-line' results to determine which state variables would be good fatigue detectors. By inspection, a 'yes', 'no', or 'inconclusive' was assigned to each case depending on the level of separation recorded. If the plot, such as Figure 4.8, showed the correct separation for more than

60% of the maneuver duration a 'yes' would be noted. If the plot showed separation from 40-60% an 'inconclusive' designation would be assigned. When the separation was less than 40% of the maneuver duration, or the 'rested' data was higher in magnitude than the 'tired' data a 'no' would be given to that particular case. The same metrics were used to analyze the standard deviation plots as well. Figure 4.11 illustrates an example of when the standard deviation of the variable was considered to be a fatigue detector, and Figure 4.12 is an example of when a particular case would have been assigned a 'no' designation.
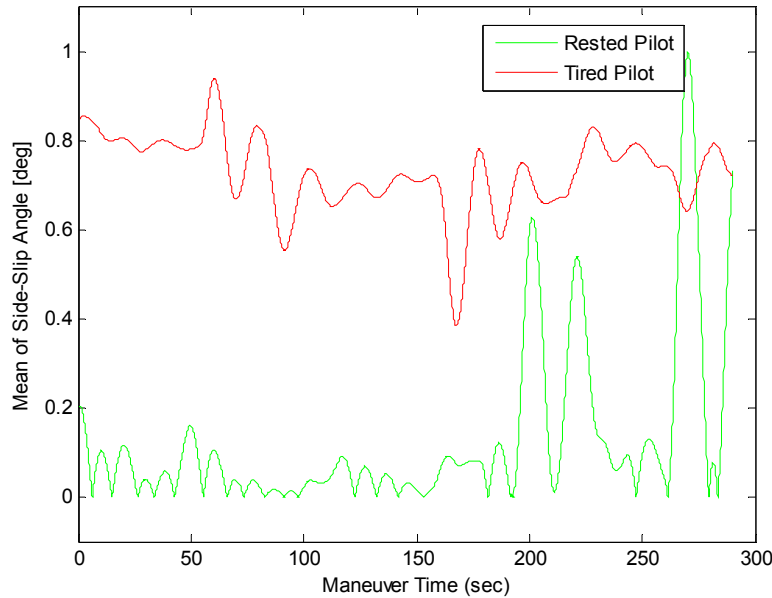

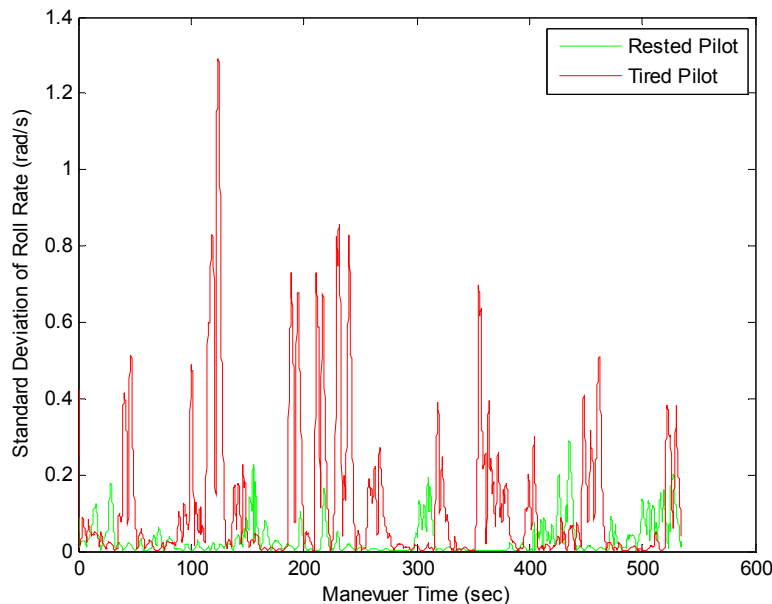**Figure 4.10:** Pilot #3 Maneuver 1 – 'On-Line' Mean of Side-Slip Angle

Figure 4.11: Pilot #2 Maneuver 1 - 'On-line' Standard Deviation of Roll Rate
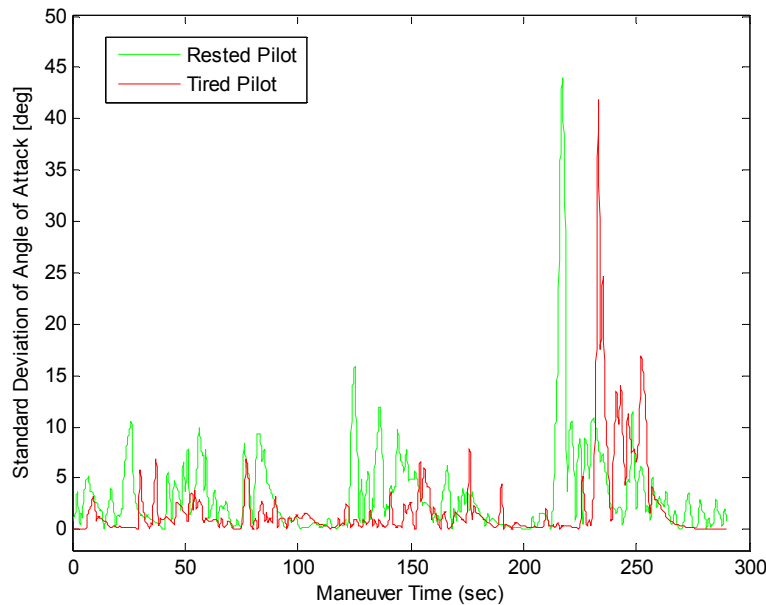
Figure 4.12: Pilot #1 Maneuver 1 – 'On-Line' Standard Deviation of Angle of Attack

No real conclusion can be made from Figure 4.12. It even appears that most of the time the 'rested' data is above the 'tired' data. When the state variable plots looked like Figure 4.12 for all three experimental pilots, the variable would be deemed unusable as a fatigue detector. Consideration was given though to the variables that followed the 'increasing' trend for even *one* of the pilots, as most of the time this *one* came from the most experienced pilot.

Conclusions drawn from plots such as Figures 4.8-4.12 gave basically the same results seen in Table 4.6 in regard to which state variables showed promise as fatigue detectors. The results from the 'on-line' and 'off-line' tests showed which variables were the best fatigue detectors for each of the maneuvers. The usage of these results will be discussed further in the Composite Parameters section.

4.5 Fourier Transform Based Analysis

An additional set of candidate fatigue detectors could be defined based on the Fourier Transform[22] of the state and control variables. This approach is supported by the hypothesis that separation between the 'rested' and 'tired' could be reflected in the spectrum of the pilot plus aircraft system. The objective was to identify if significant changes in the spectrum occur showing a difference between a 'rested' and 'tired' pilot, as well as which of the variables would capture these effects best. Therefore, within a plot of the Fourier Transform, such as Figure 4.13, magnitude and frequency were noted when there was a very distinct peak or separation between the two data sets.
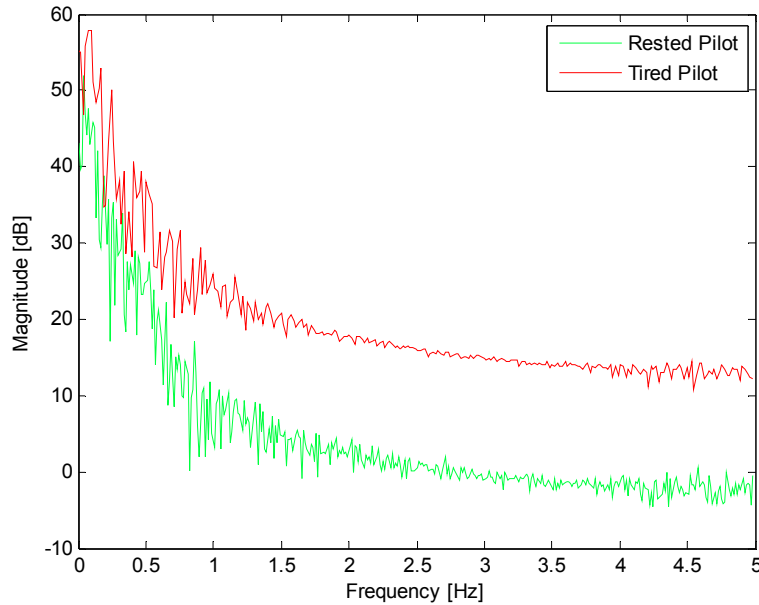
Figure 4.13: Pilot #2 Maneuver 1 - Fourier Transform of Roll Angle

Figure 4.13 illustrates that when the pilot is 'tired' the amplitudes for basically all sinusoids in the set are higher than when 'rested'. Difference in amplitude for sinusoids of the same frequency creates potential for another type of fatigue detector. A possible use of this information could be to set an amplitude threshold for the identified sinusoids. When the amplitude crosses the threshold a 'fatigue' signal could then be sent to a warning system. That is just one potential use for the Fourier Transform of the tracking errors, but due to time constraints of this research effort the Fourier Transform data was not used in any detection scheme discussed. However, it is believed that further analysis could provide promising results relating the Fourier Transform of state variables to fatigue detection.

4.6 Composite Detection Parameters

From the 'off-line' and 'on-line' tests, no *one* candidate fatigue detector followed the increasing trend from 'rested' to 'tired' for all pilots and all maneuvers. Therefore, several detectors were grouped together based on the idea that the overall magnitude of the *set* will increase in the presence of a 'tired' pilot. For example, say a composite parameter was composed of angle of attack (α), roll angle (φ), and yaw angle (ψ). If the tracking error for angle of attack and roll angle followed the increasing trend while yaw angle decreased, the sum of the three together would still give an overall increase.

The composite parameters consisted of a single row vector of weights which were different for each maneuver. The standard deviation and mean values of the tracking errors were made column vectors and put into a matrix. Then the dot product was taken of the weights and matrix to form the composite parameters as in equation 4.2.

$$CP = W \cdot \begin{bmatrix} m_{TE} & STD_{TE} \end{bmatrix} \qquad\qquad 4.2$$

The standard deviation of the tracking errors, due to its nature, was smaller in magnitude than the mean of the tracking errors. In order for both to have the same importance scaling was needed. Each variable's tracking error values for the entire length of the maneuver were divided by its own maximum tracking error value present throughout the maneuver. This put every variable's standard deviation and mean on a scale from 0 to 1 making the two have equal input into the composite parameter. Units of the composite parameters were also considered as they were not the same for each variable. The scaling method used cancelled out the units for each individual variable. This meant that each variable's values were scaled properly and unitless allowing them to be grouped in any combination.

Each state and control variable within the composite had different fatigue detection success rates, so each was given its own weight. The weights were determined based on their individual success. The highest weight was given to the variable with the greatest fatigue detection potential. Adding weights in this manner helped ensure that maximum separation of the 'rested' and 'tired' data sets was achieved.

The following are the composite parameters used for the different types of maneuvers:

$$CP_{SLF} = m_\beta + 3STD_\alpha + STD_\beta + STD_r + STD_\theta + 2STD_\varphi + STD_\psi \qquad 4.3$$

$$CP_{T45} = m_\beta + m_p + STD_\alpha + 3STD_\beta + 2STD_p + STD_q + 2STD_\theta + 2STD_\varphi + STD_\psi \qquad 4.4$$

$$CP_{T5} = 3m_\beta + m_\varphi + 3STD_\alpha + STD_\beta + STD_r + STD_\theta + 2STD_\varphi + STD_\psi \qquad 4.5$$

$$CP_{PD} = m_v + 1.5m_\varphi + m_\psi + STD_v + STD_\alpha + STD_\theta + STD_{rud_y} \qquad 4.6$$

$$CP_{RD} = 2m_\varphi + m_\psi + 1.5STD_\varphi \qquad 4.7$$

4.7 Detection Scheme I ~ Heuristics Based Binary Logic

The analysis of the composite parameters time histories has revealed good separation capabilities between the 'rested' and 'tired' cases and provided compelling evidence that real-time, on-board detection schemes, based on such parameters, could be successfully developed.

The first detection scheme was designed relying on fixed thresholds. Current and past samples of the composite parameter values were compared against the thresholds and heuristics based binary logic was used to support a three outcome decision process: pilot is 'rested', 'tired', or the situation is 'inconclusive'.

Step one in the algorithm was to determine a 'rested' or 'tired' threshold. The mean output of the composite variable was calculated for the 'rested' and 'tired' data for a given maneuver. Then these two values were averaged in order to get the threshold which is illustrated in Figure 4.14. The threshold is what the algorithm would use when determining whether the pilot was 'rested' or 'tired'.
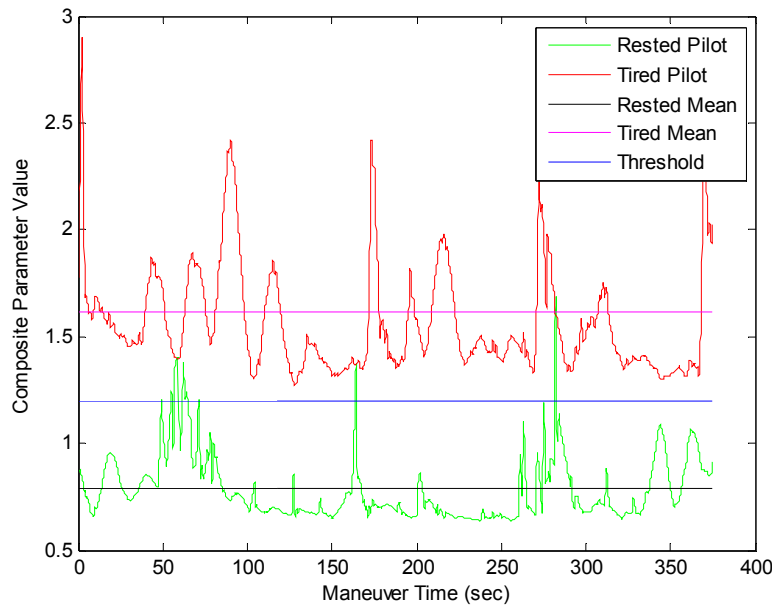
Figure 4.14: Pilot #2 Maneuver 1 – Output of Composite Parameter

      The algorithm used in Detection Scheme I consisted primarily of a series of 'if' statements as shown in Figure 4.15. The Matlab® code used for the implementation of Detection Scheme I was included in Appendix D.

      The inputs to the algorithm were the composite parameter values. These values were then given a +1, -1, or 0 depending on its relation to the threshold. A narrow band around the threshold (eps = .1) was defined in order to prevent the output from jumping from a +1 to -1 since there were values of the composite variable that were close to the threshold. For example if the pilot was tired and one data point was just below the threshold it would be undesirable for the algorithm to output a 'rested' decision based on this one data point.

      Then a 3-D matrix was filled with the +1,-1, and 0 values. Each matrix had 'n' rows, 5(m) columns, and was 100(k) units deep. The determination of the values for 'm' and 'k' came from trial and error testing of different numbers to see which amount worked the best for the three experimental pilots' data. Using too few data points made the algorithm too sensitive to the small jumps present in the above figure. Conversely, if too many data points were used then the pilot could potentially become tired and it would go unnoticed by the algorithm putting the pilot in danger of an accident. The first value was entered in position (1,1,1), the second in (1,1,2) until (1,1,100) in which the next data point would be placed in (1,2,1). When the position (1,5,100) was filled, the next data point would be placed in the first position of the next row, or (2,1,1). The data was entered in this manner until the matrix was full.
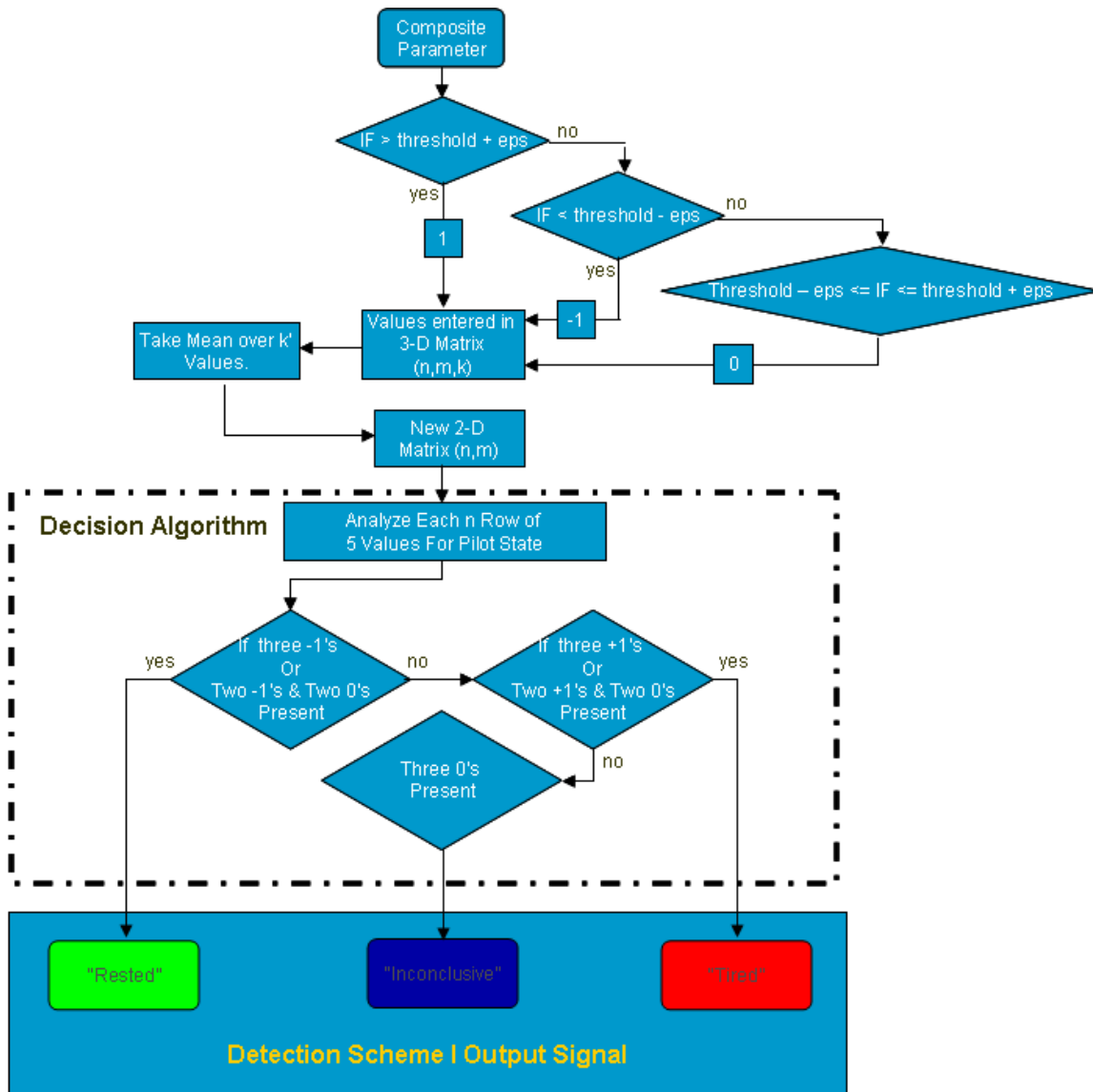
Figure 4.15: Flow Diagram of Detection Scheme I

The algorithm then took the mean of the 'k' values (e.g. (1,1,1) to (1,1,100)) which reduced the 3-D matrix to a 2-D matrix. Then the algorithm would look at the five values in each row to make a 'rested', 'tired', or 'inconclusive' determination of the pilot's condition. If three of the five values were +1 then a 'tired', or +1, output was made by the algorithm. Likewise, if there were three -1's or three 0's the output would be 'rested' (-1) or 'inconclusive' (0) respectively. If there were two pairs of values present within the five, the algorithm's decision would depend on which values were paired. If two +1's and two -1's were present the algorithm would yield and 'inconclusive' (0). If either two +1's or two -1's were present with two 0's then the decision would be either 'tired' (+1) or 'rested' (-1) respectively.

4.8 Detection Scheme II ~ Fuzzy Logic

Pilot fatigue, as any other phenomenon or condition produced by biological/physiological activity can be characterized as continuous and gradual. Therefore, binary logic in general may not be able to adequately characterize a pilot's condition in all situations. For these reasons a second algorithm for fatigue detection was implemented using fuzzy logic[23] which added an extra level of complexity to the overall algorithm. Fuzzy logic is a form of artificial intelligence that can make a decision in a similar manner to how humans make decisions based on knowledge of the present circumstances. Fuzzy logic uses membership functions to convert a crisp input to fuzzy input. The fuzzy input is used in conjunction with the inference rules, which are based on 'knowledge' previously mentioned, to produce a fuzzy output. The fuzzy output then goes through another membership function and gets transformed back into a crisp output. Figure 4.16 illustrates the fuzzy logic based Detection Scheme II algorithm. The Matlab® code used for the implementation of this detection scheme was included in Appendix D.
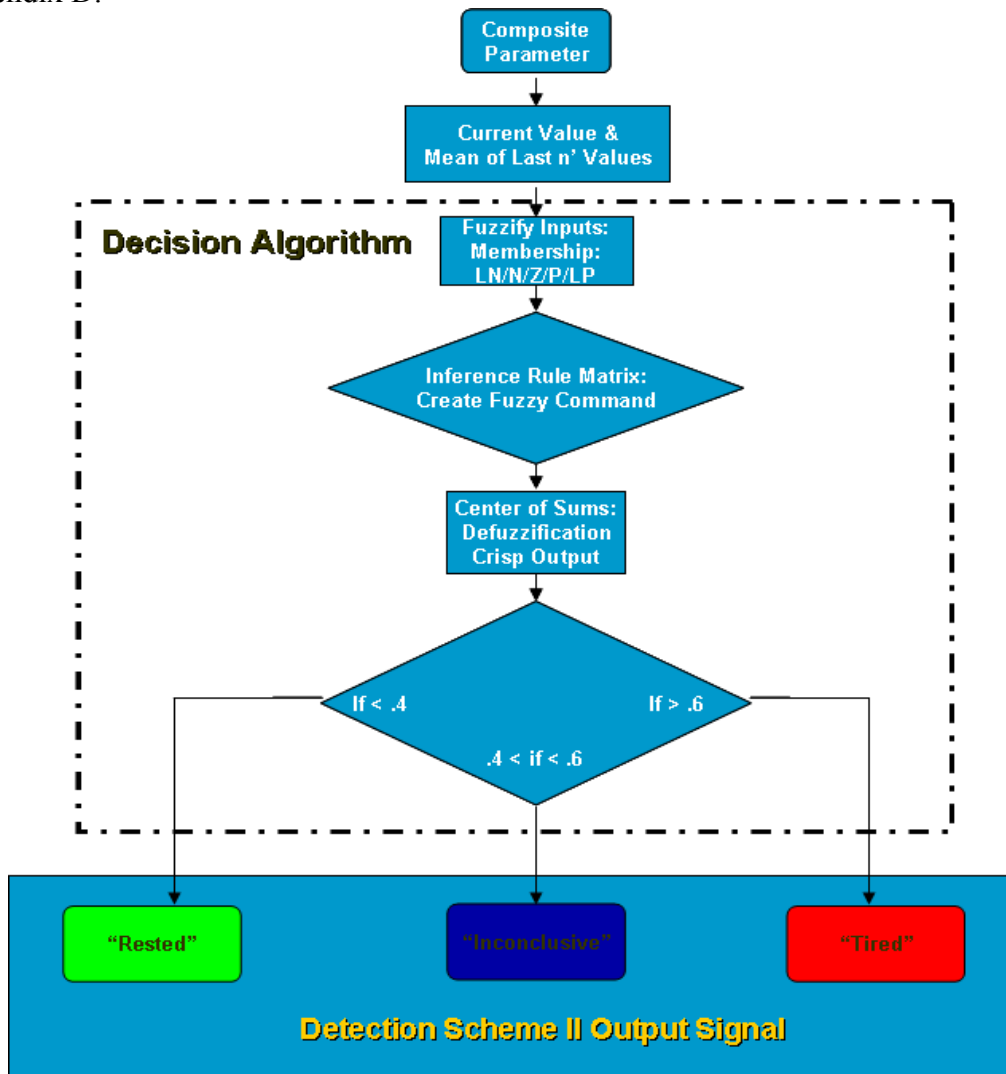
Figure 4.16: Flow Diagram of Detection Scheme II

In this application, the crisp input would be the current value of the composite parameter as well as an average over the last 200 samples. The 200 value was determined by trial and error and was determined to be the best value to filter out the jumps in the data, as described for Detection Scheme I, based on the data from the three experimental pilots. The values are sent through membership function to 'fuzzify' them based on their distance away from threshold on either side. The five intervals and their corresponding centers were defined as large negative (LN) -.3, negative (N) -.15, zero (Z) 0, positive (P) .15, and large positive (LP) .3 as illustrated in Figure 4.17.
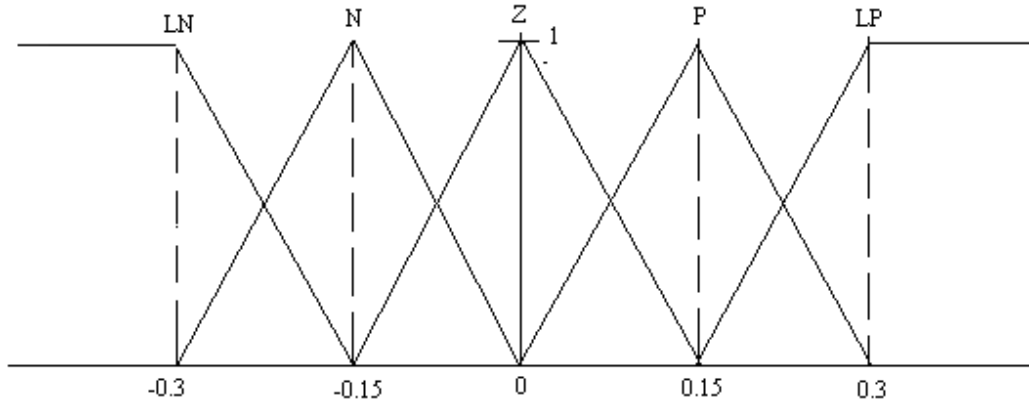

Figure 4.17: Membership Function Used to Create the 'Fuzzy Input'

The intervals side by side overlapped each other by a certain amount. Each internal interval ranged from the center of the interval below to the center of interval above. The intervals were given a triangular membership function which means that the center of a given interval means maximum membership, and as the value moves further away from the center the membership value decreases linearly to zero as it approaches the center of the interval on either side. Both the current and average values would be compared to the membership function in order to determine what intervals the values belonged to and a degree of its belonging. For example, if the current value of the composite parameter was above the threshold at a measure of .17, it would belong to both the positive and large positive intervals but at different levels of belonging. In the case of a .17 value it would belong to the positive interval more than the large positive interval because .17 is closer to .15 than .3. The same procedure was used for the average of the last 200 values of the composite parameter.

The next step of the algorithm was to determine the fuzzy command. The inference rule matrix, defined by the user, creates the fuzzy command based on the output from the membership function. The inference rule matrix used can be seen in Figure 4.18.

Average \ Current		LN	N	Z	P	LP
	LN	R	R	R	R	R
	N	R	R	R	R	I
	Z	R	I	I	I	T
	P	I	T	T	T	T
	LP	T	T	T	T	T

Figure 4.18: Fuzzy Logic Inference Rule Matrix

If the current composite parameter value is .17 and the average from the pervious 200 is also .17, the membership function would yield each belonging to both the P and LP intervals. The fuzzy command would then correspond to the four cells circled in red in Figure 4.19.

Average \ Current		LN	N	Z	P	LP
	LN	R	R	R	R	R
	N	R	R	R	R	I
	Z	R	I	I	I	T
	P	I	T	T	T	T
	LP	T	T	T	T	T

Figure 4.19: Fuzzy Command Example

The inference rule matrix would create a fuzzy command which was a collection of either 'rested' (R), 'tired' (T), or 'inconclusive' (I) determinations depending on the output from the membership function. The numerical value for each cell in the matrix was computed by multiplying the membership values of both inputs. Since there were five membership intervals an array of these membership five values were created for each input. Then the two arrays were multiplied together in order to get a 5x5 matrix that was mapped over the inference rule matrix so that the numerical values would now correspond to the proper decision that should be made.

The final step was to 'defuzzify' the fuzzy command in order to get a crisp output. Because there are three different decisions possible within the inference rule matrix there are three intervals in the membership function for the fuzzy command; one for 'rested'(-1), 'inconclusive'(0), and the last for 'tired'(+1) as illustrated in Figure 4.20.

These intervals were also defined with triangular membership functions for each interval. The center-of-sums method with scaled areas was used to 'defuzzify' the command. The areas are the areas of the triangles for each interval. Using the cells boxed in red for that example, the numerical values of each cell would be multiplied by the corresponding area for that decision. These scaled areas were summed and divided by the combined total areas. The quotient then becomes the crisp output.
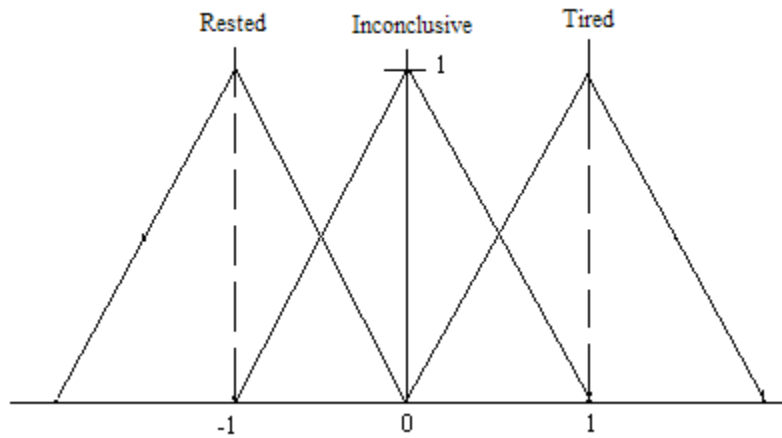
Figure 4.20: Membership Function Used to Create the Crisp Output

The crisp output of the fuzzy logic algorithm which ranged from -1 to +1 was scaled to go from 0 to 1. The scale was interpreted as a percentage 'tired'. Therefore, if the crisp output was a .85 then the pilot was considered 85% tired. Since the algorithm in Detection Scheme I gave either a -1, 0, or +1 for each classification of 'rested', 'inconclusive', or 'tired' respectively, a final step was added to the fuzzy algorithm. It was decided that if the output fell within .4 to .6 the % tired was too weak to make a concrete determination either way. Therefore, if the output was within this range an 'inconclusive' decision was made. Conversely, if the output was below .4 the pilot was said to be 'rested', and the pilot was considered 'tired' if the output was above .6. This extra step was needed in order to compare the two detection schemes directly.

Chapter 5

Results

5.1 Detection Scheme I ~ Heuristics Based Binary Logic

Testing showed that fatigue could be detected quite well for the steady state maneuvers and the coordinated turns without turbulence and moderately well for the roll doublets. The success rates of Detection Scheme 1 for classifying the condition of the pilot can be seen in Table 5.1. Table 5.2 shows for which pilots and maneuvers separation of the 'rested' and 'tired' data was achieved through the composite parameters.

Table 5.1: Success Percentages of Detection Scheme I in Identifying a 'Rested' or 'Tired' Pilot for the Different Types of Maneuvers

Maneuver	Success Rate
Steady State Flights	70%
Coordinated Turns	70%
Roll Doublet	60%
Pitch Doublet	40%
Steady State Flights w/ Turbulence	0%
Coordinated Turns w/ Turbulence	0%

Table 5.2: Summary of Success of Both Composite Parameter Separation and Accurate Pilot Condition Identification for Detection Scheme I

Detection Scheme I ~ Heuristics Based Binary Logic					
	Pilot #1	Pilot #2	Pilot #3	Pilot #4	Pilot #5
	Separation	Separation	Separation	Separation	Separation
Steady	Bad	Good	Good	Good	Good
Turn 45	Good	Good	Good	Good	Bad
Turn 5	Good	Bad	Good	Bad	Good
Steady Turb	Bad	Bad	Bad	Bad	Bad
Turn Turb L	Bad	Bad	Bad	Bad	Bad
Turn Turb R	Bad	Bad	Bad	Bad	Bad
Roll Doublet	Bad	Good	Bad	Good	Good
Steady	Bad	Good	Good	Bad	Good
Steady Turb	Bad	Bad	Bad	Bad	Bad
Pitch Doublet	Good	Bad	Bad	Bad	Good

'Good' was a metric assigned to situations when a distinct separation existed between the 'rested' and 'tired' composite variable data sets as well as positive identification by the detection scheme of both 'rested' and 'tired' for their corresponding data sets. Figures 5.1 and 5.2 are characteristic of most of the 'Good' classifications for the composite parameter and the output of Detection Scheme I.

Figure 5.1: Pilot #2 Maneuver 1 – Output of Composite Parameter
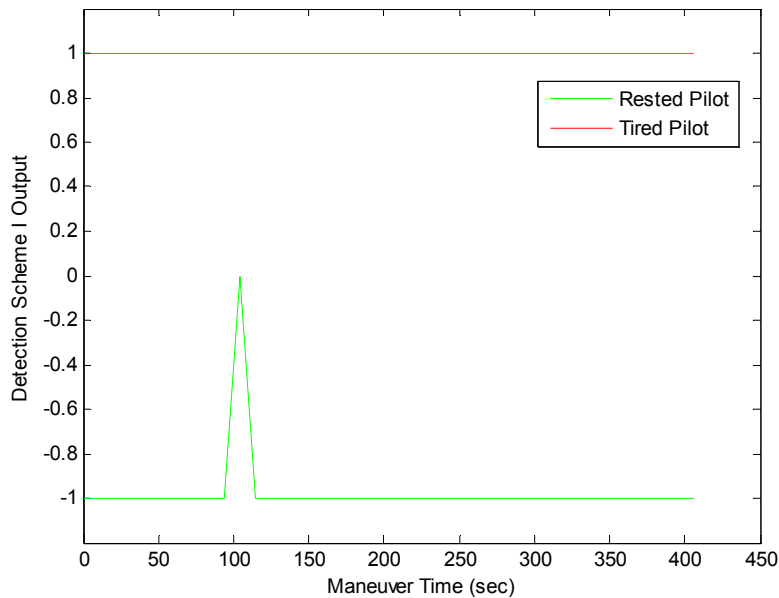
Figure 5.2: Pilot #2 Maneuver 1 – Output of Detection Scheme I

In Figure 5.1 there is a distinct separation between the 'rested' and 'tired' data produced from the composite parameter. Then based upon this separation, the detection scheme identified both 'rested' and 'tired' sets of data according to Figure 5.2. The detection scheme was able to correctly identify the tired data throughout the entire maneuver. For the 'rested' data however, there was one case in which the composite parameter value overshot the threshold for about 10-15 seconds, but still the detection scheme made the correct decision. As described in Methodology (Chapter 4), it would be

undesirable for a 'tired' decision to be made under these circumstances since it is clear that the pilot is 'rested'. The inconclusive output from the detection scheme is what accounts for these types of situations.

There were a few instances when the output plots were not as good as in Figures 5.1 and 5.2, but still a 'Good' classification was given. Figures 5.3 and 5.4 are examples of when this occurred.

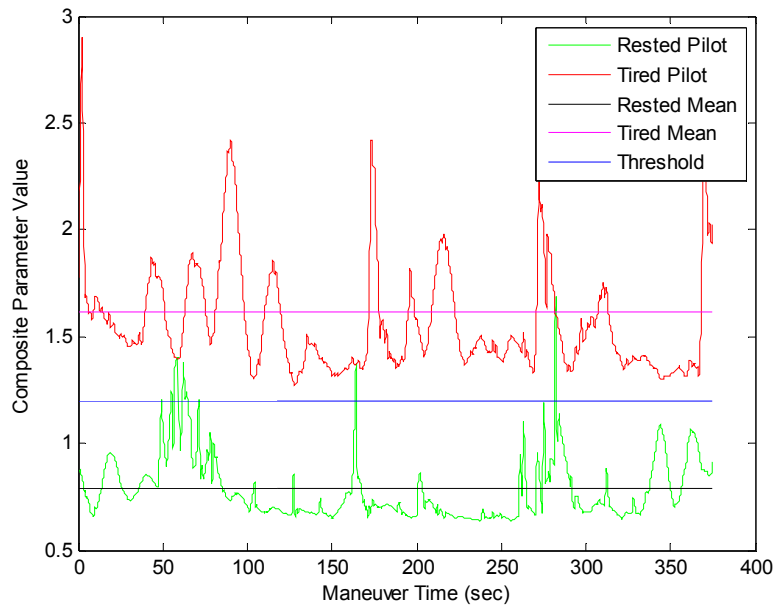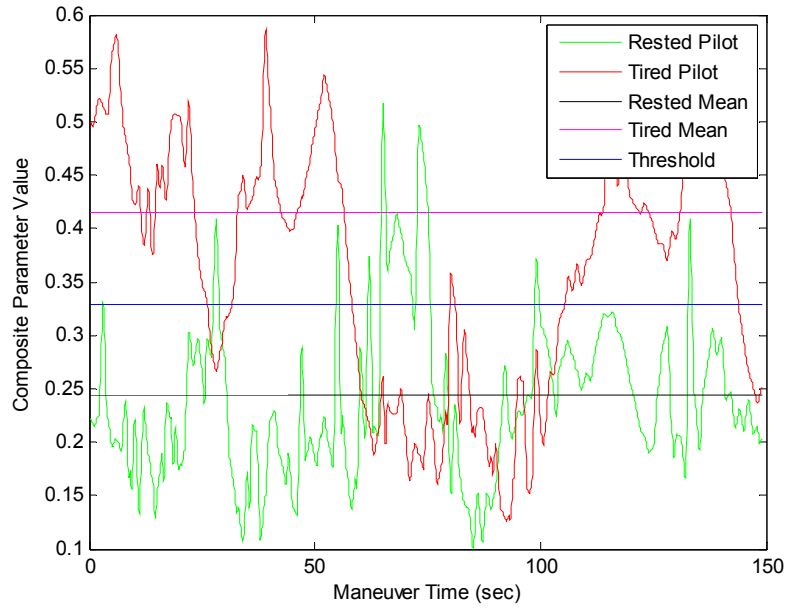**Figure 5.3:** Pilot #4 Maneuver 1 – Output of Composite Parameter
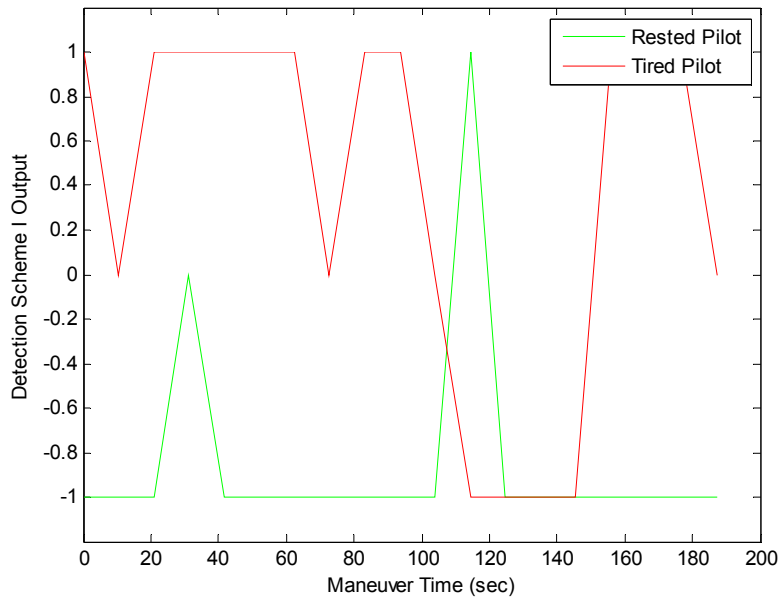

Figure 5.4: Pilot #4 Maneuver 1 – Output of Detection Scheme I

It can be observed that Figures 5.3 and 5.4 do not provide results quite as good as seen in Figures 5.1 and 5.2. Even still, there is separation for nearly 60% of the maneuver which is why a 'Good' classification was given to plots that looked like Figures 5.3 and 5.4. Also the detection scheme worked quite well in describing what the data from the composite variable actually looked like. In the time when the 'tired' data went well below the threshold for a longer period of time the scheme was able to detect it. The difference between the 'inconclusive' decision and the 'rested' decision related to the 'tired' data has to do with the sensitivity of the algorithm. The 'rested' decision was only made when the composite parameter value was below the threshold longer than the acceptable time within the algorithm. The 'inconclusive' decision was made when the composite parameter value crossed the threshold, but for the allowable amount of time as stated before.

A 'Bad' classification was given when the composite variable did not show separation and therefore the detection scheme was not able to correctly identify the pilot's condition. This occurred for every maneuver completed in the presence of turbulence. Figure 5.5 clearly shows how random the output from the composite parameter was. The turbulence introduced overshadowed any variance that could otherwise be seen between the 'rested' and 'tired' pilot, which created problems for the detection scheme. Figure 5.6 shows how the detection scheme kept jumping back and forth between a 'rested' and 'tired' decision. Detection Scheme I, and II, relies on the ability of the composite parameter to separate the data which it could not do for maneuvers in turbulence. Therefore neither scheme was able to successfully classify the pilot as 'rested' or 'tired in presence of turbulence. Figures 5.5 and 5.6 display the composite parameter values and the output of Scheme I respectively for a maneuver performed in turbulence. Such plots were characteristic of all maneuvers completed during turbulence.

Figure 5.5: Pilot #1 Maneuver 4 – Output of Composite Parameter
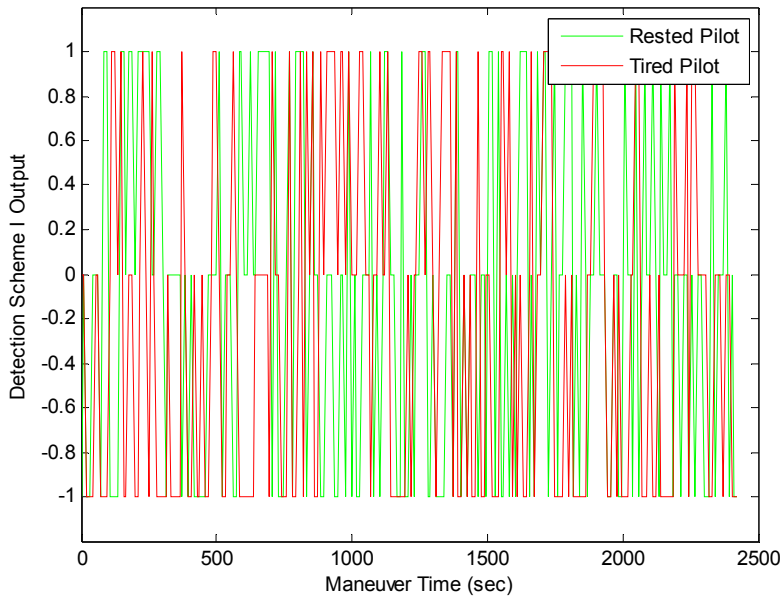
Figure 5.6: Pilot #1 Maneuver 4 – Output of Detection Scheme I

For comparison, the same composite variable was used for maneuvers 3 and 5 with the only difference being the introduction of turbulence in maneuver 5. Figure 5.7 shows that the composite parameter worked quite well in separating the 'rested' and 'tired' data. However, the same composite parameter was unable to perform well in the presence of turbulence as shown in Figure 5.8. Figures 5.9 and 5.10 are the detection scheme outputs for maneuvers 3 and 5 respectively.
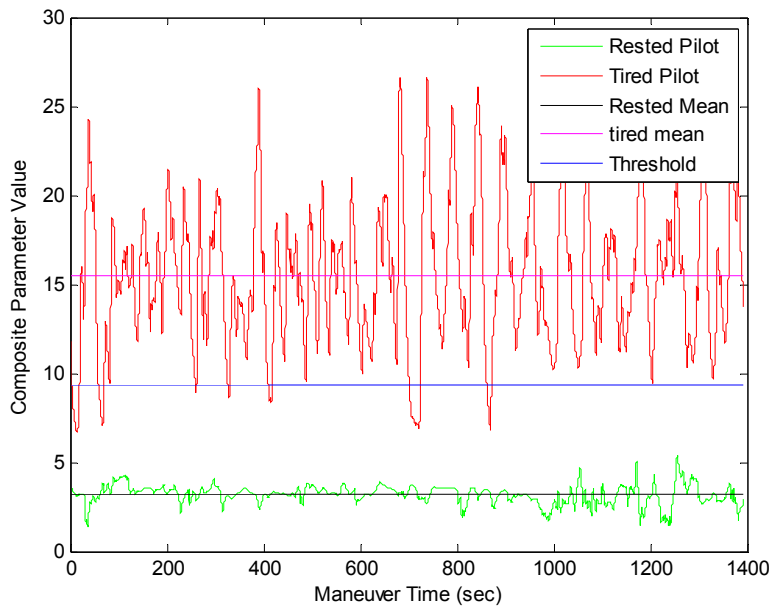
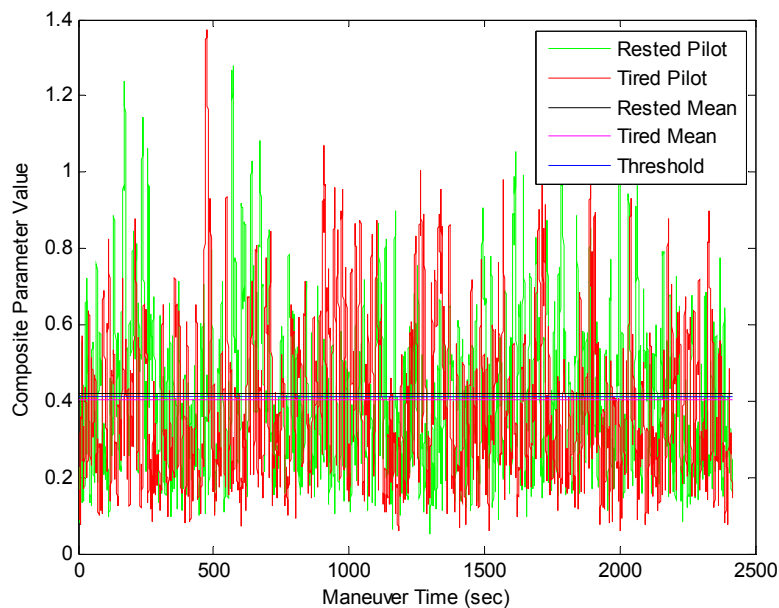**Figure 5.7:** Pilot #5 Maneuver 3 – Output of Composite Parameter
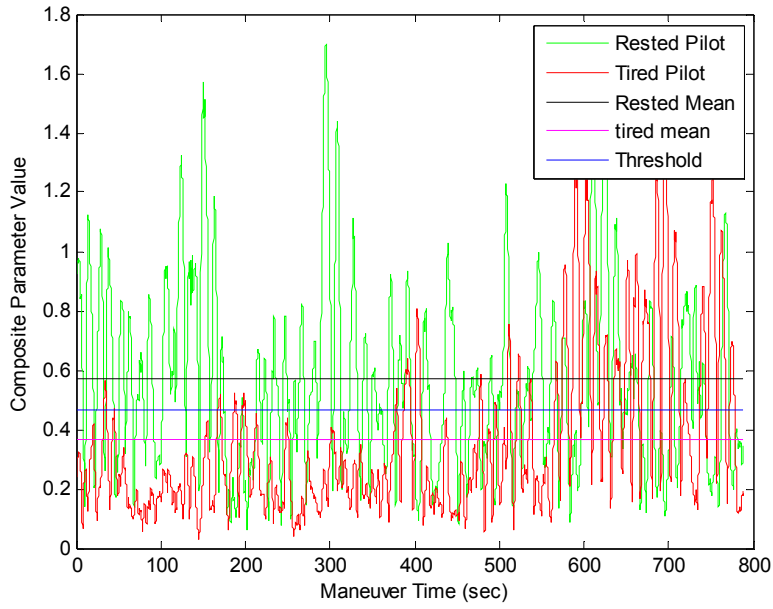
Figure 5.8: Pilot #5 Maneuver 5 – Output of Composite Parameter
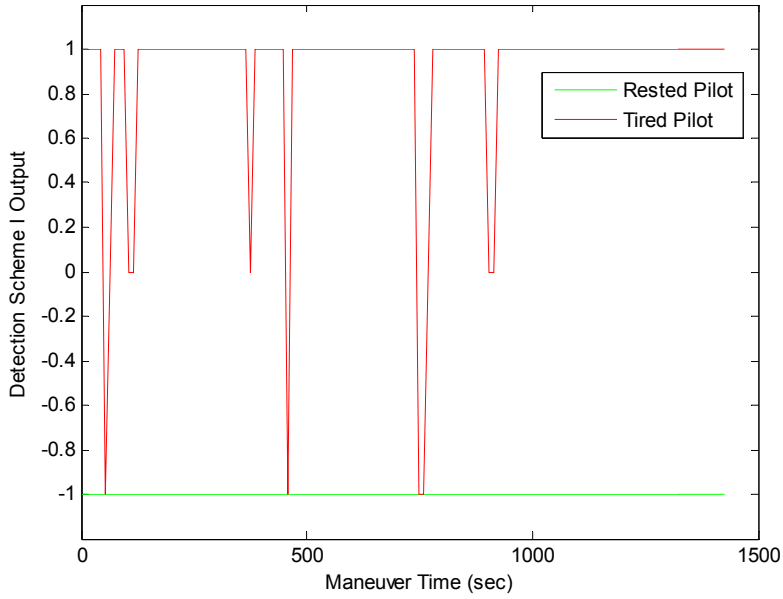
Figure 5.9: Pilot #5 Maneuver 3 – Output of Detection Scheme I
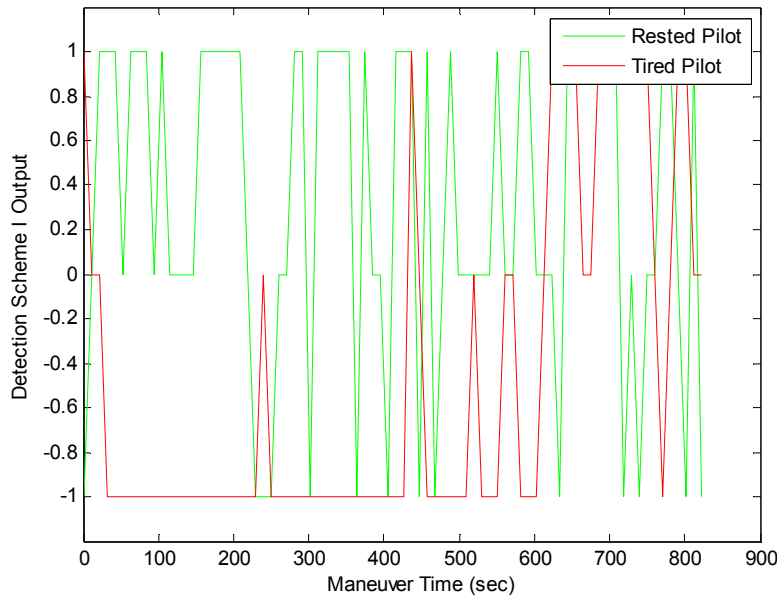
Figure 5.10: Pilot #5 Maneuver 5 – Output of Detection Scheme I

5.2 Detection Scheme II ~ Fuzzy Logic

Testing of the fuzzy logic algorithm provided results similar to that of Detection Scheme I with the increase in success rates for steady state flight maneuvers and coordinated turns without turbulence. In addition, the fuzzy logic algorithm was able to accurately classify whether or not the pilots were 'rested' or 'tired' 100% percent of the time for the roll doublet. Table 5.3 shows the success rates from Detection Scheme II, and Table 5.4 shows the classifications of 'Good' or 'Bad' detection for Scheme II. The 'Good' and 'Bad' classifications were given in the manner as for Scheme I. Also in Table 5.4 is a column that shows the result of an integral calculation between the 'tired' and 'rested' composite parameter output. The number in this column describes the area between the 'tired' and 'rested' data. Since the 'tired' data should have higher values, a positive integral calculation means that data point for data point the 'tired' data was higher than the 'rested' data which was desired. So the higher the positive value of the integral the better the separation of 'rested' and 'tired' composite parameters should be.

Table 5.3: Success Percentages of Detection Scheme II in Identifying a 'Rested' or 'Tired' Pilot for the Different Types of Maneuvers

Maneuver	Success Rate
Steady State Flights	80%
Coordinated Turns	80%
Roll Doublet	100%
Pitch Doublet	40%

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Table 5.4: Summary of Success of Both Composite Parameter Separation and Accurate
Pilot Condition Identification for Detection Scheme II

	Detection Scheme II (Fuzzy Logic)									
	Pilot #1		**Pilot #2**		**Pilot #3**		**Pilot #4**		**Pilot #5**	
	Integral	Separation	Integral	Separation	Integral	Separation	Integral	Separation	Integral	Separation
Steady	-4293	Bad	3522	Good	1497	Good	340	Good	9204	Good
Turn 45	2648	Good	4340	Good	5271	Good	3884	Good	-33799	Bad
Turn 5	47210	Good	61581	Good	12985	Good	-30220	Bad	17721	Good
Roll Doublet	339	Good	285	Good	1879	Good	2438	Good	1633	Good
Steady	-884	Bad	5621	Good	1118	Good	1044	Good	3962	Good
Pitch Doublet	5654	Good	-390	Bad	-11528	Bad	-1094	Bad	13137	Good

It is important to remember that both Detection Schemes I and II used the same input data, which was the output of the composite parameters. It was expected that the fuzzy logic algorithm in Detection Scheme II would perform better since it is more sophisticated than Detection Scheme I.

Figure 5.11 shows the fuzzy output using the input data from Figure 5.1. As discussed in Methodology (Chapter 4) the fuzzy logic algorithm would output a range of values from 0 to 1 corresponding to how 'tired' the pilot should be considered. The data in this plot was then filtered (refer to Methodology) so it could be compared directly to the output of Detection Scheme I for the same maneuver and pilot. The final output of Detection Scheme II related to Figure 5.11 can be seen in Figure 5.12.
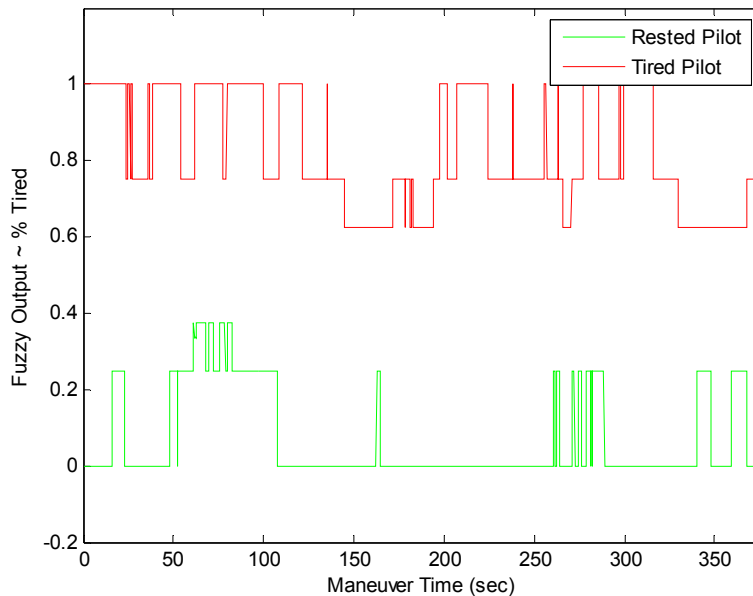
Figure 5.11: Pilot #2 Maneuver 1 – Output of Fuzzy Logic Algorithm
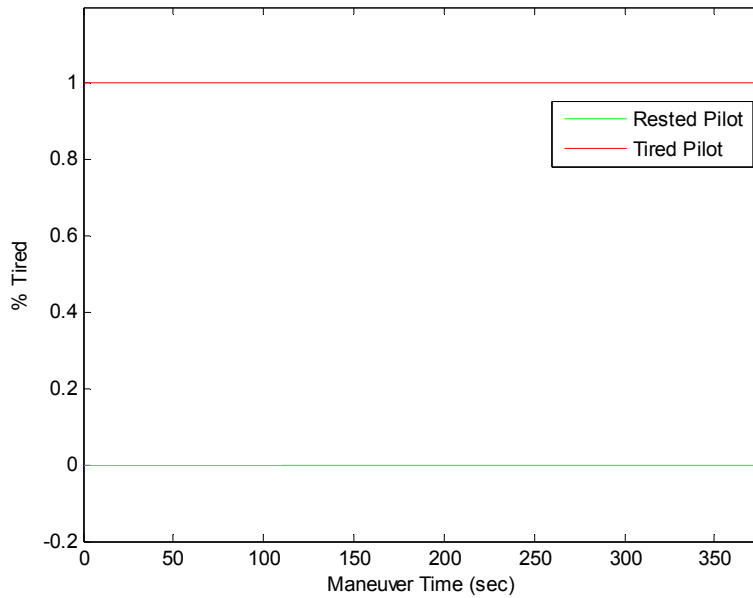
Figure 5.12: Pilot #2 Maneuver 1 – Output of Detection Scheme II

In Figure 5.2 there is an 'inconclusive' decision made by Scheme I, but Scheme II was able to make the correct 'rested' decision.

In comparison to Figure 5.4, Detection Scheme II provided similar results to that of Detection Scheme I.
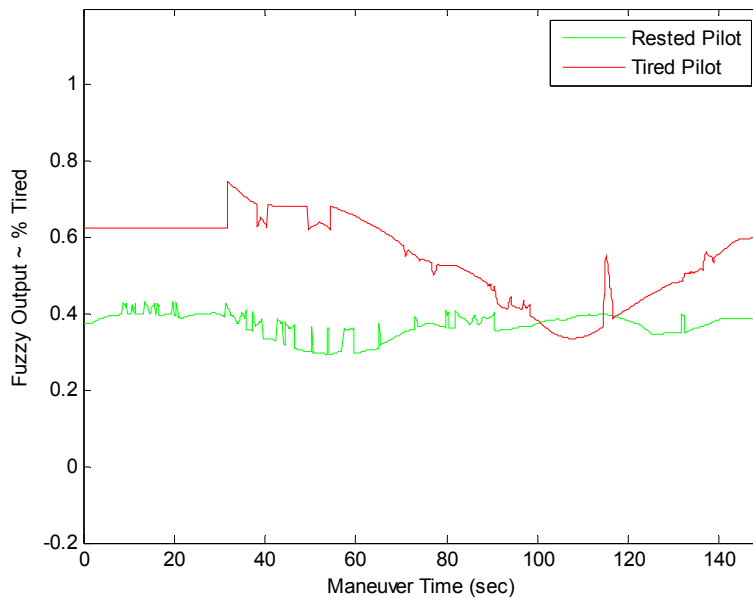
Figure 5.13: Pilot #4 Maneuver 1 – Output of Fuzzy Logic Algorithm

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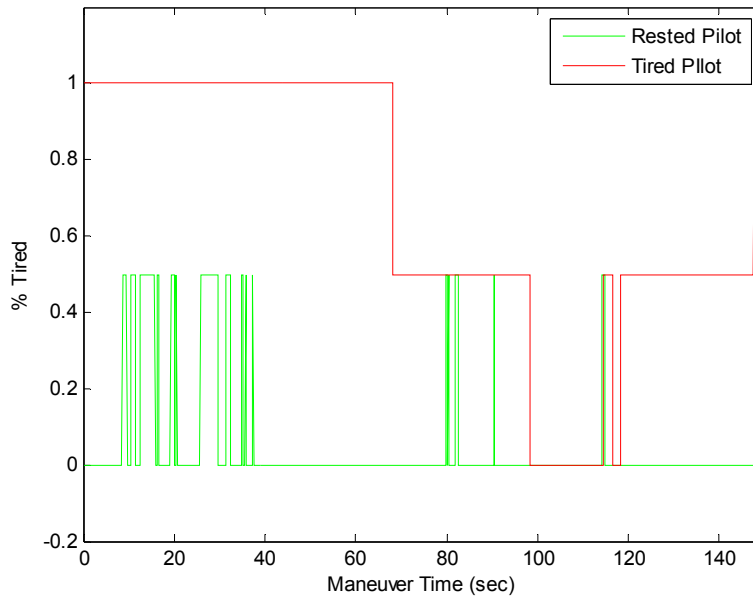
Figure 5.14: Pilot #4 Maneuver 1 – Output of Detection Scheme II

Figure 5.14 shows that Detection Scheme II was able to make the correct decision for the 'tired' data in the first part of the maneuver. Also, at no time during the maneuver was the 'rested' data mistakenly considered 'tired' by Scheme II as it was in Scheme I.

Detection Scheme II also made a significant improvement in classifying a 'rested' and 'tired' pilot for the roll doublet. According to Table 5.1 Scheme I was unable to make a correct classification for the roll doublet for Pilot 2, but Table 5.4 shows that Scheme II was able to make the correct classification. Figures 5.15 and 5.16 show the difference in results of Scheme I and Scheme II.
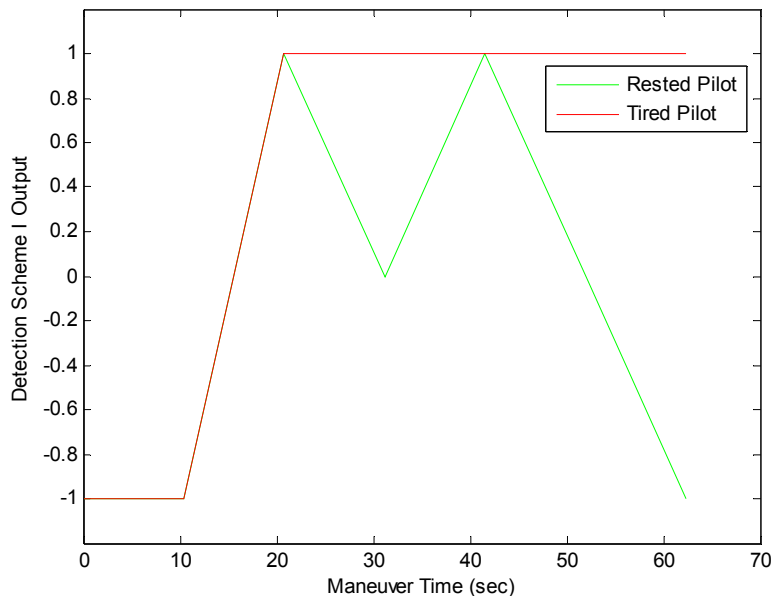
Figure 5.15: Pilot #2 Maneuver 7 – Output of Detection Scheme I
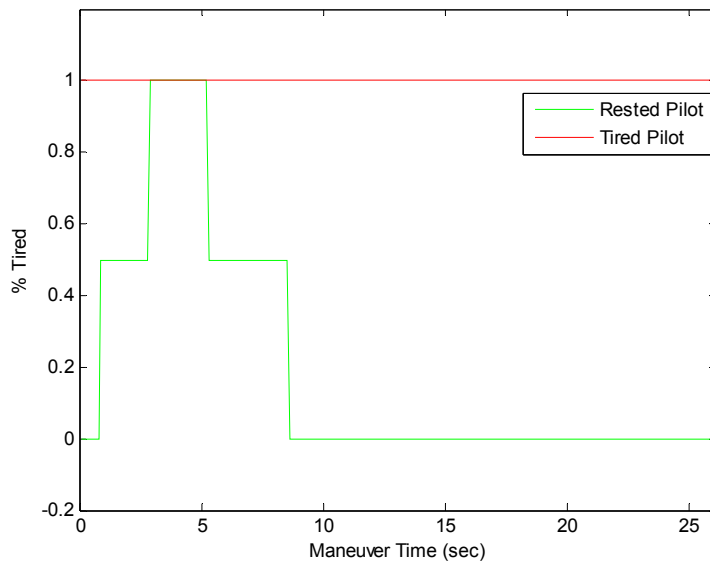
Figure 5.16: Pilot #2 Maneuver 7 – Output of Detection Scheme II

Scheme II was able to make the correct 'rested' and 'tired' decisions for both sets of data for the majority of the roll doublet maneuver. Scheme I, however, had more trouble. The reason for the success of Scheme II precipitates from the ability of the fuzzy logic algorithm to look at both the current value of the composite parameter in addition to the average value over last set of values. Scheme I only makes its decision based upon the average of the composite parameter's values as discussed in Methodology (Chapter 4).

Detection Scheme II had the same results as Scheme I discussed for maneuver 3. Scheme II was able to make the correct 'rested' and 'tired' classifications of the pilot's condition for maneuver 3. Figure 5.17 shows the output of Scheme II for maneuver 3.

Figure 5.17: Pilot #5 Maneuver 3 – Output of Detection Scheme II

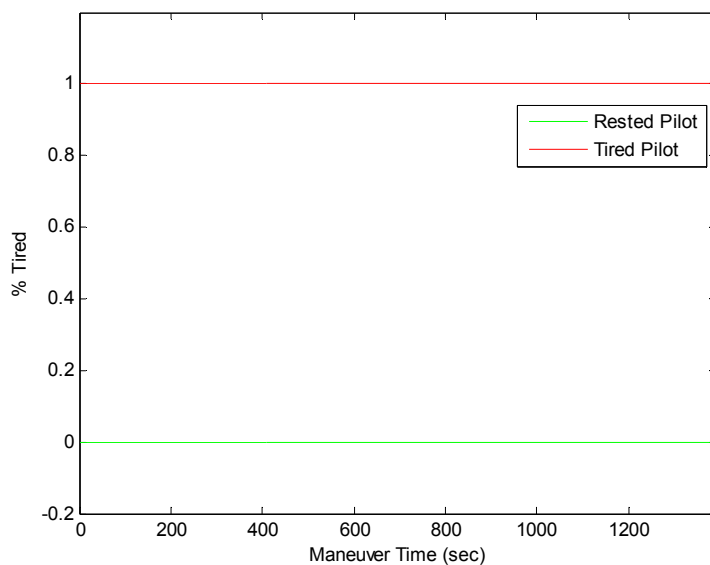As Figure 5.9 is the output of Scheme I and Figure 5.17 is the output of Scheme II, it is clear that Scheme II was again better at classifying the pilot's condition.

5.3 Detection Scheme III ~ Fuzzy Neural Network

Preliminary analysis of a third detection scheme was investigated as an alternative approach. The fuzzy neural network[24] showed promising results that this type of detection scheme could correctly classify a 'rested' or 'tired' pilot using composite parameter data.

A neural network uses a group of decision making modules referred to as 'neurons' to produce an output based upon a given input, hence the name 'neural network'. Just as neurons within the human brain, these neurons need to be trained. The neural network is 'trained' using training data that will be characteristic of future data the network would be likely to encounter. The training data, a set of inputs and their corresponding outputs, is shown to the network so that each neuron can calibrate itself to produce the correct output. As can be concluded, the neural network's success is related to how well the training data represents all data that the network will encounter.

The fuzzy logic toolbox within Matlab® has a preprogrammed function called 'anfis' which can be described as Adaptive Neuro-Fuzzy Inference System[21]. This function uses a user defined set of training data to produce a fuzzy neural network. Each neuron then uses its own Matlab® designed fuzzy logic system, as described in Methodology (Chapter 4) for Detection Scheme II, to decide what the correct output should be for any given input, which should be similar to the inputs in the training data.

For application in this research effort, the first step was to define the set of training data for the 'anfis' function. It was decided that pilot #2's data for maneuver 1 would be the best training data as pilot #2 was the most skilled of the three experimental pilots and good results were produced for steady state flight conditions. The training data consisted of the composite parameter output for the 'rested' and 'tired' data sets and their corresponding output of either -1 or +1 respectively. The 'anfis' function requires a two column matrix; column one for input values and column two for output values. The first half of the input column was the 'rested' composite parameter values while the second half was that of the 'tired' values. Likewise, the first half of the output column was filled with -1 values and the second half was filled with +1 values.

Figure 5.18 shows the training data from pilot #2 and the output of fuzzy neural network for same input data used to train the network. The shift of the data upward halfway through Figure 5.18 represents when the input shifts from 'rested' to 'tired' data. This shows that the fuzzy neural network was capable of detecting when the pilot changed from a 'rested' to a 'tired' condition for this set of data. However, this output is not quite as crisp as the output from Schemes I and II.
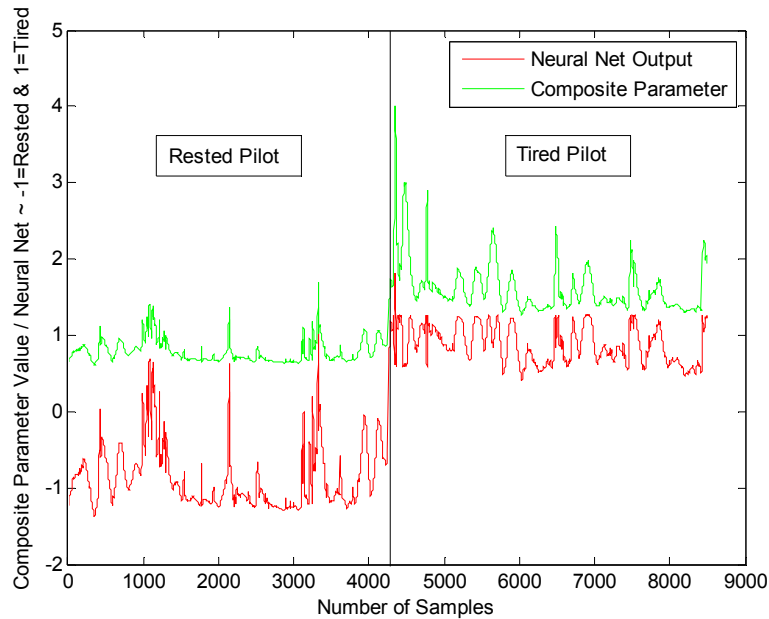
Figure 5.18: Pilot # 2 Maneuver 1 – Output of Fuzzy Neural Network Using Composite Parameter Input

Conceptually, it was expected that the fuzzy neural network would show improvement over the other two detection schemes as this method is even more sophisticated than the fuzzy logic algorithm in Scheme II. There were two main reasons why the fuzzy neural network did not show a great improvement over the other two schemes in this application. The first was related to the amount of training data available. This study only involved three test pilots which did not provide enough data for proper training of the network. This lack of training data would not allow the network to fully develop, which kept it from working to its full potential. The second issue was the pilot variability. The composite parameter values varied in magnitude from pilot to pilot, even when the same maneuver was considered. It was believed that this range of values is what limited the networks functionality. However, a possible solution to this problem would be to develop a method to group the composite parameter values for the 'rested' and 'tired' conditions so that each fell within the same range of values. For example, if all the composite parameter values for the 'rested' pilot condition of a steady level flight were within 2 and 3, then the network would be able to make a more precise determination of the pilot's condition.

It should be noted that even with the limited amount of training data and the variability among the pilots, the fuzzy neural network was able to make a decent determination of the pilot's condition as seen in Figure 5.18. Solutions to these two problems could greatly increase the fuzzy neural network's ability to accurately detect pilot fatigue and should be included in any future investigation.

Chapter 6

Conclusions

In this research effort, the use of aircraft state and control variables for pilot fatigue detection was investigated. Standard deviation and mean of the state and control variables' tracking errors were considered as candidate detectors. Tests showed an increase from a 'rested' to 'tired pilot in mean and standard deviation of tracking errors.

The variables that showed the most promising results were selected as possible fatigue detectors. Composite parameters consisted of weighted sums of possible fatigue detectors dependent upon the type of maneuver considered. The composite parameters were designed to separate the 'rested' and 'tired' data.

Detection schemes were developed to determine the condition of the pilot as 'rested' or 'tired' using the composite parameter's output. Detection Scheme I used heuristic based binary logic to make its pilot condition determination. Detection Scheme II used fuzzy logic to classify the pilots' condition.

Detection Schemes I and II showed promising results for fatigue detection of steady level flight conditions along with coordinated turns. Results also showed that Scheme II was more successful. The fuzzy logic based scheme provided determination of the pilot's condition with higher rates of success.

Maneuvers in the presence of turbulence were also investigated. However, the composite parameters were unable to separate the 'rested' and 'tired' data. It was believed that the high level of turbulence caused too much randomness within state and control variable values. This randomness overshadowed any chance of detecting the smaller changes within the data caused by fatigue. As both detection schemes relied upon the composite parameters they were unable to make the correct decision regarding the pilots' condition.

In doublet maneuvers only Detection Scheme II was able to correctly classify the condition of the pilots. This was largely due to how the two schemes were designed along with how little time it took to complete the maneuvers. Scheme I was unsuccessful because it only made a decision based upon an average value of the composite parameter over a certain window of time, which meant that if the composite parameter did not perfectly separate the data for these short maneuvers good results were unlikely. Scheme II used both the average of the composite parameter values over a window of time and the composite parameter's current value for decision making. Results showed that this technique provided much better pilot classification for the roll doublet, as well as for the other maneuvers. However, for the pitch doublet neither scheme was able to produce the correct pilot condition determination for a significant percentage of the cases.

From the preliminary results of the fuzzy neural network it was determined that this method should be investigated further. One issue encountered with this method was that there was not enough data to properly train the network. The lack of training data reduced the ability of the network to make a crisp determination of the pilot's condition. Pilot variability also reduced the networks performance due to different ranges of the composite parameter values for each pilot. However, the network's output does show visible separation of the two data sets. It is believed that with an increase in the amount

of training data available and more research that this method could prove to detect fatigue quite well.

Though positive results of fatigue detection were achieved through Detection Schemes I and II, future work will be needed to refine them in order to apply them to a 'real life' application. Further investigation into the composite parameters is needed, even though preliminary analysis showed promising results. Additional research, such as the Fourier Transform approach mentioned, could provide other methods to separate the 'rested' and 'tired' data.

Currently both detection schemes rely upon the type of maneuver already being established; each will have to work in conjunction with another system that can determine what type of maneuver the pilot is completing. Further investigation will also have to take into account what will actually happen when a 'tired' or 'rested' signal is triggered by the detection scheme. Also in some maneuvers both signals would have been triggered, though for only short periods of time throughout the maneuver. It must be determined how to deal with situations such as this since the ultimate goal will be countermeasures that would correct for the pilot's reduced ability to control the aircraft when the pilot is determined to be fatigued. Inevitably, these countermeasure systems would use the output of the detection schemes to prevent fatigue related accidents.

Preliminary results have shown compelling evidence supporting the hypothesis that fatigue detection is possible using state and control variables. Moreover, Detection Schemes I and II have shown that fatigue can be 'detected' during flight. It is hoped that the research presented in this thesis will be continued and ultimately be implemented in future aircraft as a means of preventing fatigue related accidents.

Chapter 7

Lessons Learned

Throughout this research effort valuable lessons were learned that could benefit further research into this subject. The first lesson deals with data collection techniques. When the pilots are flying the flight scenario, it is important to specify and monitor the precise time at which each maneuver is supposed to start and when it actually starts. This would considerably reduce the data processing effort and allow the analysis of response delays which could have potentially high relevance for fatigue detection.

A second lesson involves the varying levels of piloting experience. As the pilot's experience level increased so did the success of the composite parameters in separating the 'rested' and 'tired' data. The premise was that when a pilot with greater experience was rested he would be able to fly a near 'perfect' maneuver. Therefore, when the pilot was fatigued the lower performance level would be more visible in the data and could therefore be readily detected. Conversely, an inexperienced pilot would perceivably not be able to fly this 'perfect' maneuver. This extra variance in the 'rested' data could close the gap between the composite variable outputs of the 'rested' and 'tired' data. The additional variance would be similar in nature to the added 'noise' from turbulence.

Thirdly, more techniques of analyzing the state variables could be implemented. As this research showed positive results in its preliminary analysis, only the standard deviation and mean were calculated for the state variables as part of this effort. Future research should explore other techniques such as the Fourier Transform mentioned.

As discussed in Methodology (Chapter 4), scaling factors were used to get each state variable's output on the same 0 to 1 scale. The method of using the maximum value of each state variable for the entire length of the maneuver seemed to work well, but other methods of scaling may improve results even further. While the scaling did not seem to affect the composite parameter's ability to separate the two data sets, the average values of the composite parameters varied from pilot to pilot in 'rested' and 'tired' conditions. If these averages could be brought closer together it would make designing a universal fatigue detection scheme more feasible since the distance between the threshold and composite parameter output would be more consistent from pilot to pilot.

Finally, a limited number of tests were permitted for this study. A considerably larger number of tests would be necessary to gain deeper insight into the effects of pilot fatigue on the dynamic response of the pilot aircraft system, and to achieve statistical significance for any conclusions.

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Appendix A

Additional Figures

Figure A1: Pilot #1 Maneuver 2 – Output of Detection Scheme I

Figure A3: Pilot #2 Maneuver 2 – Output of Detection Scheme I

Figure A2: Pilot #1 Maneuver 2 – Output of Detection Scheme II
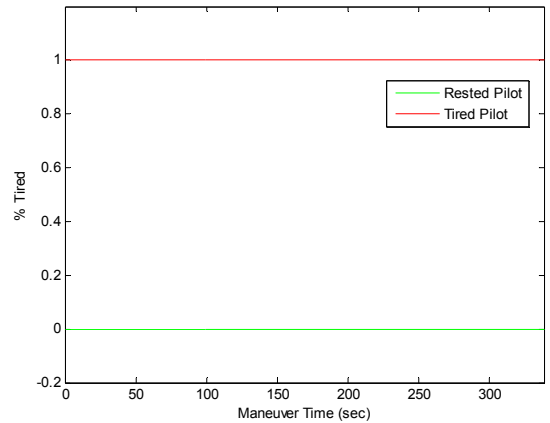
Figure A4: Pilot #2 Maneuver 2 – Output of Detection Scheme II
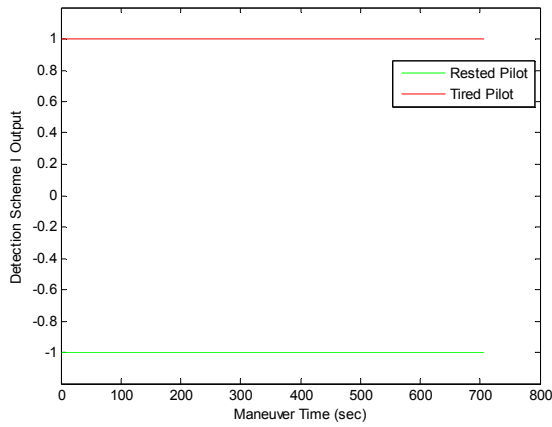
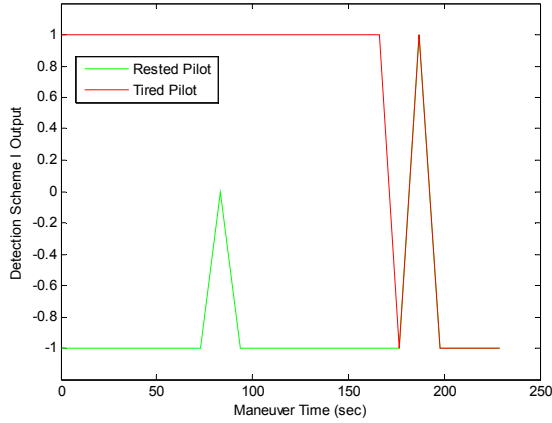**Figure A5:** Pilot #2 Maneuver 8 – Output of Detection Scheme I

Figure A6: Pilot #2 Maneuver 8 – Output of Detection Scheme II

Figure A7: Pilot #3 Maneuver 1 – Output of Detection Scheme I
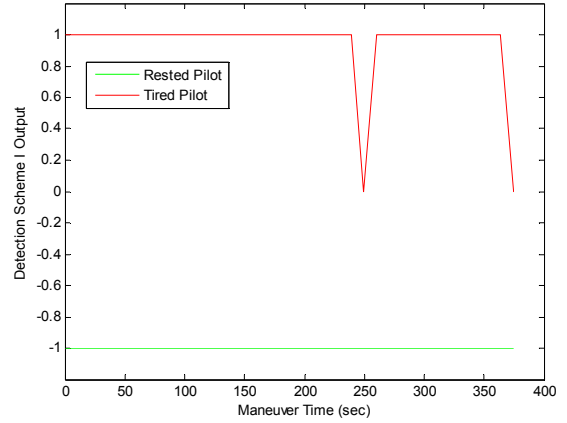

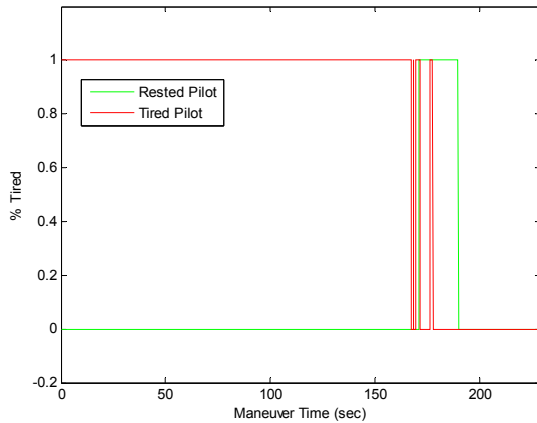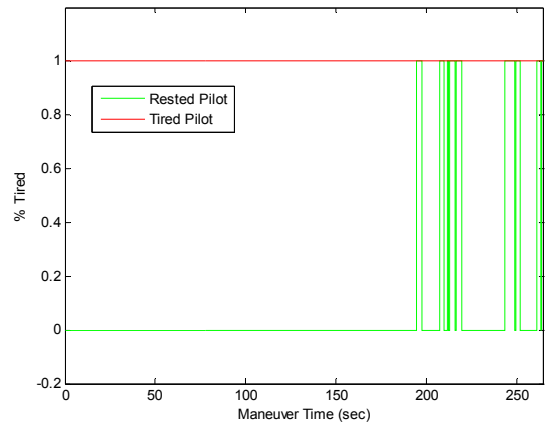**Figure A8:** Pilot #3 Maneuver 1 – Output of Detection Scheme II
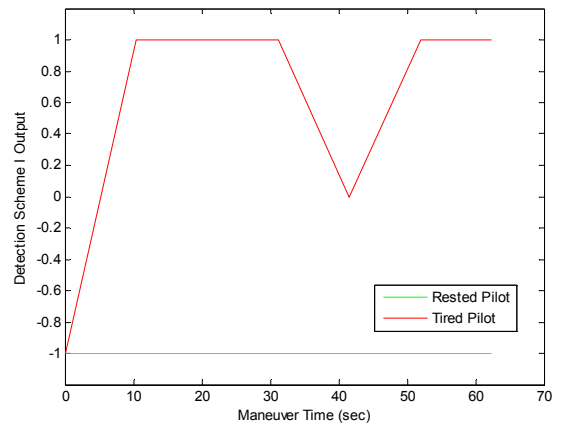
Figure A9: Pilot #4 Maneuver 7 – Output of Detection Scheme I
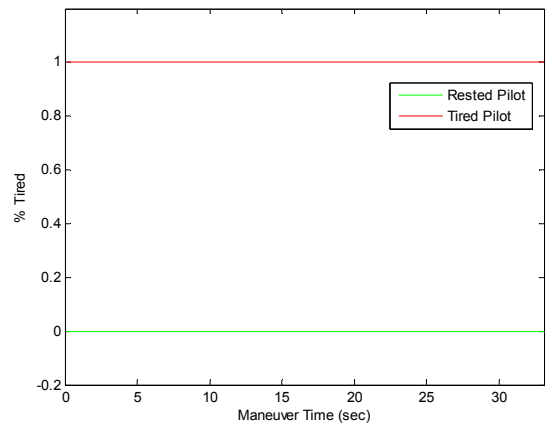
Figure A10: Pilot #4 Maneuver 7 – Output of Detection Scheme II

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Appendix B

Test Pilot Questionnaires

Pilot Fatigue Investigation
Test #1 – Rested Pilot
After Test Questionnaire

Name: Pilot #1
Date: 10/11/2006

Please respond to the following questions:

1. When did you go to bed the night before the test? *1:00am*
2. When did you wake up the morning of the test? *7:00am*
3. Did you have a good sleep? If not, explain. *Yes*
4. Did you feel fully rested the morning of the test? *Yes*
5. Did you take any medication within 24 hours prior to the test? *Yes, antihistamines*
6. How much coffee or caffeine drinks did you have during the 12 hour interval prior to the test? *none*
7. Do you think you have performed your piloting tasks during the test at full/normal/rested capacity, or better, or worse? Explain. *Was rested, however, slightly affected by allergies*
8. What were the most challenging moments/tasks during the test? *Landing after coming out of turbulence*
9. Did you make any errors during the test? Explain. *Yes, landing was long, lost track of time*
10. Were there moments when your performance was not as good as usual? Explain. *Landing, having just come out of turbulence, was still at 140kts, 5000ft (3700 above ground level)*

Pilot Fatigue Investigation
Test #2 – Tired Pilot
After Test Questionnaire

Name: Pilot #1
Date: 10/21/2006

Please respond to the following questions:

1. When did you wake up this morning? *7:30am*
2. Did you have a sleep during the day? *No*
3. Did you take any medication within 24 hours prior to the test? *No*
4. How much coffee or caffeine drinks did you have during the 12 hour interval prior to the test? *none*
5. Do you think you have performed your piloting tasks during the test as expected given the fact that you are very tired, better, or worse? Explain. *Yes, very tired, landing was bad*
6. What were the most challenging moments/tasks during the test? *Landing and turbulence*
7. Did you make any errors during the test? Explain. *Yes, too much throttle on landing*
8. Were there moments when your performance was not as good as expected? Explain. *Just after turbulence gained too much altitude, landing, too much throttle*
9. What do you think the effects of being tired are on your performance as a pilot? *Over compensated for things that should have received minimal response*

Name: Pilot #2
Date: 10/10/2006

Please respond to the following questions:

1. When did you go to bed the night before the test? *11:00pm*
2. When did you wake up the morning of the test? *8:00am*
3. Did you have a good sleep? If not, explain. *Yes*
4. Did you feel fully rested the morning of the test? *Yes*
5. Did you take any medication within 24 hours prior to the test? *No*
6. How much coffee or caffeine drinks did you have during the 12 hour interval prior to the test? *one*
7. Do you think you have performed your piloting tasks during the test at full/normal/rested capacity, or better, or worse? Explain. *Full capacity*
8. What were the most challenging moments/tasks during the test? *N/A*
9. Did you make any errors during the test? Explain. *Nothing unusual*
10. Were there moments when your performance was not as good as usual? Explain. *Yes because I was digging through section 1.*

Pilot Fatigue Investigation
Test #2 – Tired Pilot
After Test Questionnaire

Name: Pilot #2
Date: 10/26/2006

Please respond to the following questions:

1. When did you wake up this morning? *7:30am*
2. Did you have a sleep during the day? *No*
3. Did you take any medication within 24 hours prior to the test? *No*
4. How much coffee or caffeine drinks did you have during the 12 hour interval prior to the test? *none*
5. Do you think you have performed your piloting tasks during the test as expected given the fact that you are very tired, better, or worse? Explain. *Yes*
6. What were the most challenging moments/tasks during the test? *Landing*
7. Did you make any errors during the test? Explain. *No*
8. Were there moments when your performance was not as good as expected? Explain. *No*
9. What do you think the effects of being tired are on your performance as a pilot? *It is hard to concentrate when I am very tired*

Pilot Fatigue Investigation
Test #1 – Rested Pilot
After Test Questionnaire

Name: Pilot #3
Date: 10/10/2006

Please respond to the following questions:

1. When did you go to bed the night before the test? *11:00pm*
2. When did you wake up the morning of the test? *7:30am*
3. Did you have a good sleep? If not, explain. *Yes*
4. Did you feel fully rested the morning of the test? *Yes*
5. Did you take any medication within 24 hours prior to the test? *No*
6. How much coffee or caffeine drinks did you have during the 12 hour interval prior to the test? *8oz. at 6pm the night before*
7. Do you think you have performed your piloting tasks during the test at full/normal/rested capacity, or better, or worse? Explain. *Normal*
8. What were the most challenging moments/tasks during the test? *Landing*
9. Did you make any errors during the test? Explain. *Yes, let the nose gear touch at same time as mains*
10. Were there moments when your performance was not as good as usual? Explain. *Yes, I came in at too steep an approach*

Pilot Fatigue Investigation
Test #2 – Tired Pilot
After Test Questionnaire

Name: Pilot #3
Date: 10/20/2006

Please respond to the following questions:

1. When did you wake up this morning? *7:00am*
2. Did you have a sleep during the day? *No*
3. Did you take any medication within 24 hours prior to the test? *No*
4. How much coffee or caffeine drinks did you have during the 12 hour interval prior to the test? *none*
5. Do you think you have performed your piloting tasks during the test as expected given the fact that you are very tired, better, or worse? Explain. *Yes*
6. What were the most challenging moments/tasks during the test? *Turbulence*
7. Did you make any errors during the test? Explain. *N/A*
8. Were there moments when your performance was not as good as expected? Explain. *Landing was messed up, not sure why*
9. What do you think the effects of being tired are on your performance as a pilot? *Being tired definitely degraded performance*

Name: Pilot #4
Date: 10/31/2007

Please respond to the following questions:

1. When did you go to bed the night before the test?
2. When did you wake up the morning of the test? *7:30am*
3. Did you have a good sleep? If not, explain. *Yes*
4. Did you feel fully rested the morning of the test? *Yes*
5. Did you take any medication within 24 hours prior to the test? *No*
6. How much coffee or caffeine drinks did you have during the 12 hour interval prior to the test? *Yes, 1 soda*
7. Do you think you have performed your piloting tasks during the test at full/normal/rested capacity, or better, or worse? Explain. *As expected*
8. What were the most challenging moments/tasks during the test? *Keeping level flight*
9. Did you make any errors during the test? Explain. *Overdid the 45deg band turn by 90deg*
10. Were there moments when your performance was not as good as usual? Explain. *Not really*

Pilot Fatigue Investigation
Test #2 – Tired Pilot
After Test Questionnaire

Name: Pilot #4
Date: 12/7/2007

Please respond to the following questions:

1. When did you wake up this morning? *6:00am*
2. Did you have a sleep during the day? *No*
3. Did you take any medication within 24 hours prior to the test? *No*
4. How much coffee or caffeine drinks did you have during the 12 hour interval prior to the test? *½ soda*
5. Do you think you have performed your piloting tasks during the test as expected given the fact that you are very tired, better, or worse? Explain. *A little worse, but not due to being tired, just being rusty on landing causing problems*
6. What were the most challenging moments/tasks during the test? *Turbulence*
7. Did you make any errors during the test? Explain. *On landing, I floated the plane*
8. Were there moments when your performance was not as good as expected? Explain. *No, besides landing*
9. What do you think the effects of being tired are on your performance as a pilot? *Reaction time slightly slower, nothing else really*

Pilot Fatigue Investigation
Test #1 – Rested Pilot
After Test Questionnaire

Name: Pilot #5
Date: 11/30/2007

Please respond to the following questions:

1. When did you go to bed the night before the test?
2. When did you wake up the morning of the test? *8:00am*
3. Did you have a good sleep? If not, explain. *It was okay*
4. Did you feel fully rested the morning of the test? *N/A*
5. Did you take any medication within 24 hours prior to the test? *N/A*
6. How much coffee or caffeine drinks did you have during the 12 hour interval prior to the test? *None*
7. Do you think you have performed your piloting tasks during the test at full/normal/rested capacity, or better, or worse? Explain. *Better*
8. What were the most challenging moments/tasks during the test? *Initial timing after take-off*
9. Did you make any errors during the test? Explain. *Possibly*
10. Were there moments when your performance was not as good as usual? Explain. *Landing*

Pilot Fatigue Investigation
Test #2 – Tired Pilot
After Test Questionnaire

Name: Pilot #5
Date: 12/7/2007

Please respond to the following questions:

1. When did you wake up this morning? *7:00am*
2. Did you have a sleep during the day? *No*
3. Did you take any medication within 24 hours prior to the test? *No*
4. How much coffee or caffeine drinks did you have during the 12 hour interval prior to the test? *5 sodas*
5. Do you think you have performed your piloting tasks during the test as expected given the fact that you are very tired, better, or worse? Explain. *About equal*
6. What were the most challenging moments/tasks during the test? *All about the same*
7. Did you make any errors during the test? Explain. *No huge ones*
8. Were there moments when your performance was not as good as expected? Explain. *No*
9. What do you think the effects of being tired are on your performance as a pilot? *A little sluggish on the controls and reaction time*

Instructor Pilot Interviews

Intro   **Interviewee:** <u>Chuck Gant</u>
We are trying to develop a system that detects pilot fatigue based on flight dynamics of an aircraft. A test flight pattern was designed to include steady level flight, full circle turns, and doublets with the hope that we will notice a difference in "tracking" the variables selected for a rested and tired pilot.

1. Which branch of the military did you fly for? (Army, Marines, etc) *Army*

2.   Roughly how many flight hours do you have with rotary and/or fixed wing aircraft?
        Rotary: *6000*
        Fixed wing: *1800*

3. How many different rotary/fixed wing aircraft have you flown? *25+*

4. Is there a specific aircraft that made you tired quicker? *Hughes 500 series helicopter, due to lack of hydraulic controls and stability augmentation system.*

5. Do you perceive the aircraft to respond differently when you are tired? *Fine control touch skills diminish.*

6. Does it seem like you have to work the controls more, when tired, to achieve the same aircraft performance? If so, what do you have to do "differently" to achieve the same level of performance for the same task? *Depending on the flight mode (e.g., hovering, taking off/landing, etc.) more concentration is required for precision, but I do not think the aircraft is harder to fly manually.*

7. Are there any specific maneuvers that become harder to maintain than others, such as maintaining a constant air speed, altitude, or angle of attack, or hovering? *Once again, when you are tired you must concentrate more to maintain any given parameter.*

8. What environmental conditions (sun, wind, rain, clouds, night flight, etc.) hasten your fatigue? *All of the above, especially if utilizing Night Vision devices, such as helmet mounted goggles that cause eye strain and neck fatigue.*

Intro   **Interviewee:** Chip Weakly

We are trying to develop a system that detects pilot fatigue based on flight dynamics of an aircraft. A test flight pattern was designed to include steady level flight, full circle turns, and doublets with the hope that we will notice a difference in "tracking" the variables selected for a rested and tired pilot.

1. Which branch of the military did you fly for? (Army, Marines, etc) *Army*

3. Roughly how many flight hours do you have with rotary and/or fixed wing aircraft?
   Rotary: *7~8000*
   Fixed wing: *8500*

3. How many different rotary/fixed wing aircraft have you flown? *19 fixed wing, 2 Helicopters*

4. Is there a specific aircraft that made you tired quicker? *OB1 – Nighthawk, there were so many systems (night flights)*

5. Do you perceive the aircraft to respond differently when you are tired? *Not really, maybe when learning to fly. Trim tabs helped reduce fatigue effects.*

6. Does it seem like you have to work the controls more, when tired, to achieve the same aircraft performance? If so, what do you have to do "differently" to achieve the same level of performance for the same task? *I felt like I was double checking everything. Time gets distorted and seems to speed up. 4hrs in a cockpit tends to wear on you.*

7. Are there any specific maneuvers that become harder to maintain than others, such as maintaining a constant air speed, altitude, or angle of attack, or hovering? *Instrumental approaches (landing) can be very difficult. Single pilot planes also makes flying tougher.*

8. What environmental conditions (sun, wind, rain, clouds, night flight, etc.) hasten your fatigue? *All of the above...*

Intro   **Interviewee:** Dale Kiel
We are trying to develop a system that detects pilot fatigue based on flight dynamics of an aircraft. A test flight pattern was designed to include steady level flight, full circle turns, and doublets with the hope that we will notice a difference in "tracking" the variables selected for a rested and tired pilot.

1. Which branch of the military did you fly for? (Army, Marines, etc) *Army*

2. Roughly how many flight hours do you have with rotary and/or fixed wing aircraft?
      Rotary: *12,000*
      Fixed wing: *2000*

3. How many different rotary/fixed wing aircraft have you flown? *Huey – UH1*
      (Vietnam era)

4. Is there a specific aircraft that made you tired quicker? *N/A*

5. Do you perceive the aircraft to respond differently when you are tired? *I felt like I was slowing down. My response time deteriorated. I felt sluggish.*

6. Does it seem like you have to work the controls more, when tired, to achieve the same aircraft performance? If so, what do you have to do "differently" to achieve the same level of performance for the same task? *I felt like I was over compensating due to a lack of awareness.*

7. Are there any specific maneuvers that become harder to maintain than others, such as maintaining a constant air speed, altitude, or angle of attack, or hovering? *Hovering was harder since it requires a lot of coordination of many variables. Flying instruments become more demanding.*

8. What environmental conditions (sun, wind, rain, clouds, night flight, etc.) hasten your fatigue? *In the clouds with turbulence. Rain was more of a distraction than anything else, the noise it caused gets deafening.*

Intro   **Interviewee:** <u>Ed Grueztzenmacher</u>

We are trying to develop a system that detects pilot fatigue based on flight dynamics of an aircraft. A test flight pattern was designed to include steady level flight, full circle turns, and doublets with the hope that we will notice a difference in "tracking" the variables selected for a rested and tired pilot.

1. Which branch of the military did you fly for? (Army, Marines, etc) *Army*

2. Roughly how many flight hours do you have with rotary and/or fixed wing aircraft?
    Rotary: *5000*
    Fixed wing: 20*00*

3. How many different rotary/fixed wing aircraft have you flown? *20-25, Super King, Caribou*

4. Is there a specific aircraft that made you tired quicker? *I'm 6'3" and 210lbs. so basically anything with a small cockpit.*

5. Do you perceive the aircraft to respond differently when you are tired? *When first learning to fly. Pilots tend to fixate on something when tired, your cross-checks go away and you sometimes lose track of what is going on with the airplane.*

6. Does it seem like you have to work the controls more, when tired, to achieve the same aircraft performance? If so, what do you have to do "differently" to achieve the same level of performance for the same task? *Your reaction time definitely gets reduced. Boredom is another factor. You feel like you're not as alert and the airplane tends to wander.*

7. Are there any specific maneuvers that become harder to maintain than others, such as maintaining a constant air speed, altitude, or angle of attack, or hovering? *Hovering! Visual cues are not as responsive when you're tired. Yawning and blinking a lot.*

8. What environmental conditions (sun, wind, rain, clouds, night flight, etc.) hasten your fatigue? *Night vision goggles. Weather and turbulence really drags on you.*

Matlab Codes

```
% Detection Scheme I Program
% Pilot #2
% Maneuvers:  All
% 2/26/08
% Ben Smith



% close all
% clc


%*********Retrieve Data From Simulink**********
% Steady Flight
% je_rested=n_rested(1000:5250);  %Good
% je_tired=n_tired(1000:5250);
% n_mbetar=n_m_beta_r(1000:5250);
% n_mbetat=n_m_beta_t(1000:5250);
% xxtime=1:length(n_mbetar);
% xxtime=xxtime/10;
% figure,plot(xxtime,n_mbetar,'g',xxtime,n_mbetat,'r')
% legend('Rested','Tired')
% xlabel('Maneuver Time (sec)')
% ylabel('Variable Value')
% % Turn 45 deg
% je_rested=n_rested(11:3900);    %Good
% je_tired=n_tired(11:3900);
% Turn 5 deg
% je_rested=n_rested(11:8000);
% je_tired=n_tired(11:8000);
% Steady Flight Turbulence
% je_rested=n_rested(11:11000);
% je_tired=n_tired(11:11000);
% Turn w/Turb 5 L
% je_rested=n_rested(11:6951);
% je_tired=n_tired(11:6951);
% Turn w/Turb 5 R
% je_rested=n_rested(11:3081);
% je_tired=n_tired(11:3081);
% Roll Doublet
% je_rested=n_rested(11:771);
% je_tired=n_tired(11:771);
% Steady Flight II
je_rested=n_rested(11:7231);
je_tired=n_tired(11:7231);
% Steady Flight Turb II
% je_rested=n_rested(11:25281);
% je_tired=n_tired(11:25281);
% Pitch Doublet
% je_rested=n_rested(11:1091);
% je_tired=n_tired(11:1091);


Thresh_Je=(mean(je_rested)+mean(je_tired))/2;
```

```
%**************************************
%**** Detection Scheme for Nicholas ****
% Determine how many window of 10 samples
eps=.01*Thresh_Je;
nrsample=100;
nrpacket=5;
grouping=104;
numbera=length(je_rested)/grouping;
numberb=floor(numbera);

Je_matrix_R=zeros(numberb,nrpacket,nrsample);
Je_matrix_T=zeros(numberb,nrpacket,nrsample);
% Step 1
% Determining Every Data point R/T/I
ll=1;
for i=1:numberb
    l=ll;
    for j=1:nrpacket
        for k=1:nrsample
            % Rested File
            Je_matrix_R(i,j,k)=je_rested(l);
            if Je_matrix_R(i,j,k)>=Thresh_Je+eps
                Je_matrix_R(i,j,k)=1;
            else if Je_matrix_R(i,j,k)>Thresh_Je-eps &&
Je_matrix_R(i,j,k)<Thresh_Je+eps
                Je_matrix_R(i,j,k)=0;
                else if Je_matrix_R(i,j,k)<=Thresh_Je-eps
                Je_matrix_R(i,j,k)=-1;
                    end
                end
            end
            % Tired File
            Je_matrix_T(i,j,k)=je_tired(l);
            if Je_matrix_T(i,j,k)>=Thresh_Je+eps
                Je_matrix_T(i,j,k)=1;
            else if Je_matrix_T(i,j,k)>Thresh_Je-eps &&
Je_matrix_T(i,j,k)<Thresh_Je+eps
                Je_matrix_T(i,j,k)=0;
                else if Je_matrix_T(i,j,k)<=Thresh_Je-eps
                Je_matrix_T(i,j,k)=-1;
                    end
                end
            end
            l=l+1;
        end
        l=ll+j;
    end
    ll=ll+grouping;
end

% Step 2
% Determining R/T/I for each group of 10
Je_matrix_Ra=zeros(numberb,nrpacket);
Je_matrix_Ta=zeros(numberb,nrpacket);
hipas=round(.7*nrsample);
```

```
lopas=nrsample-hipas;
for i=1:numberb
    for j=1:nrpacket
        % Rested File
        Jea=length(find(Je_matrix_R(i,j,:)<0));
        Jeam(i,j)=Jea;
        if Jea>=hipas
            Je_matrix_Ra(i,j)=-1;
        end
        if Jea<hipas && Jea>lopas
            Je_matrix_Ra(i,j)=0;
        end
        if Jea<=lopas
            Je_matrix_Ra(i,j)=1;
        end
        % Tired File
        Jeb=length(find(Je_matrix_T(i,j,:)>0));
        if Jeb>=hipas
            Je_matrix_Ta(i,j)=1;
        end
        if Jeb<hipas && Jeb>lopas
            Je_matrix_Ta(i,j)=0;
        end
        if Jeb<=lopas
            Je_matrix_Ta(i,j)=-1;
        end
    end
end

% Step 3
% Determining R/T/I Using Group of 5 using previous indicator
for i=1:numberb
    for j=2:nrpacket
        % Rested File
        if Je_matrix_Ra(i,j)>0 && Je_matrix_Ra(i,j-1)<0
            Je_matrix_Ra(i,j)=0;
        end
        if Je_matrix_Ra(i,j)==0 && Je_matrix_Ra(i,j-1)>0
            Je_matrix_Ra(i,j)=1;
        end
        if Je_matrix_Ra(i,j)>0 && Je_matrix_Ra(i,j-1)>0
            Je_matrix_Ra(i,j)=1;
        end
        if Je_matrix_Ra(i,j)<0 && Je_matrix_Ra(i,j-1)<0
            Je_matrix_Ra(i,j)=-1;
        end
        if Je_matrix_Ra(i,j)==0 && Je_matrix_Ra(i,j-1)<0
            Je_matrix_Ra(i,j)=-1;
        end
        if Je_matrix_Ra(i,j)<0 && Je_matrix_Ra(i,j-1)>0
            Je_matrix_Ra(i,j)=0;
        end
        % Tired File
        if Je_matrix_Ta(i,j)<0 && Je_matrix_Ta(i,j-1)<0
            Je_matrix_Ta(i,j)=-1;
        end
        if Je_matrix_Ta(i,j)==0 && Je_matrix_Ta(i,j-1)<0
```

```matlab
            Je_matrix_Ta(i,j)=-1;
        end
        if Je_matrix_Ta(i,j)<0 && Je_matrix_Ta(i,j-1)>0
            Je_matrix_Ta(i,j)=0;
        end
        if Je_matrix_Ta(i,j)>0 && Je_matrix_Ta(i,j-1)<0
            Je_matrix_Ta(i,j)=0;
        end
        if Je_matrix_Ta(i,j)==0 && Je_matrix_Ta(i,j-1)>0
            Je_matrix_Ta(i,j)=1;
        end
        if Je_matrix_Ta(i,j)>0 && Je_matrix_Ta(i,j-1)>0
            Je_matrix_Ta(i,j)=1;
        end
    end
end

% Step 4
% Determining R/T/I for Overall Indicator
Je_matrix_Rb=zeros(numberb,1);
Je_matrix_Tb=zeros(numberb,1);

for i=1:numberb
    % Rested File
    Jeaa=length(find(Je_matrix_Ra(i,:)<0)); %neg
    Jeaaa=length(find(Je_matrix_Ra(i,:)>0)); %pos
    Jeaaaa=length(find(Je_matrix_Ra(i,:)==0)); %I
    if Jeaa>=3
        Je_matrix_Rb(i)=-1;
    else if Jeaaa>=3
        Je_matrix_Rb(i)=1;
        else if Jeaaaa>=3
        Je_matrix_Rb(i)=0;
            else if Jeaa==2 && Jeaaa==2
            Je_matrix_Rb(i)=0;
                else if Jeaaaa==2 && Jeaa==2
                Je_matrix_Rb(i)=-1;
                    else if Jeaaaa==2 && Jeaaa==2
                    Je_matrix_Rb(i)=1;
                        end
                    end
                end
            end
        end

    end
    % Tired File
    Jebb=length(find(Je_matrix_Ta(i,:)<0)); %neg
    Jebbb=length(find(Je_matrix_Ta(i,:)>0)); %pos
    Jebbbb=length(find(Je_matrix_Ta(i,:)==0)); %I
    if Jebb>=3
        Je_matrix_Tb(i)=-1;
    else if Jebbb>=3
        Je_matrix_Tb(i)=1;
        else if Jebbbb>=3
            Je_matrix_Tb(i)=0;
```

```matlab
            else if Jebb==2 && Jebbb==2
                Je_matrix_Tb(i)=0;
                else if Jebbbb==2 && Jebb==2
                    Je_matrix_Tb(i)=-1;
                    else if Jebbbb==2 && Jebbb==2
                        Je_matrix_Tb(i)=1;
                        end
                    end
                end
            end
        end
    end
end
arraya=zeros(1,numberb);
arraya(1,1)=0;
for i=2:numberb
    arraya(i)=arraya(i-1)+grouping/10;
end
figure,plot(arraya,Je_matrix_Rb','g',arraya,Je_matrix_Tb','r')
legend('Rested Pilot','Tired Pilot')
ylabel('Detection Scheme I Output')
xlabel('Maneuver Time (sec)')
```

```matlab
% Fuzzy Logic Detection Scheme Program
% Pilot #2
% Maneuvers:  All
% 2/26/08
% Ben Smith


% close all
% clc
%************Retrieve Data From Simulink************
% Steady Flight
% jerested=n_rested(1000:5250);
% jetired=n_tired(1000:5250);
% % Turn 45 deg
% jerested=n_rested(11:3900);
% jetired=n_tired(11:3900);
% Turn 5 deg
% jerested=n_rested(11:8000);
% jetired=n_tired(11:8000);
% Steady Flight Turbulence
% jerested=n_rested(11:11000);
% jetired=n_tired(11:11000);
% Turn w/Turb 5 L
% jerested=n_rested(11:6951);
% jetired=n_tired(11:6951);
% Turn w/Turb 5 R
% jerested=n_rested(11:3081);
% jetired=n_tired(11:3081);
% Roll Doublet
% jerested=n_rested(11:771);
% jetired=n_tired(11:771);
% Steady Flight II
% jerested=n_rested(11:7231);
% jetired=n_tired(11:7231);
% Steady Flight Turb II
% jerested=n_rested(11:25281);
% jetired=n_tired(11:25281);
% Pitch Doublet
% jerested=n_rested(11:1091);
% jetired=n_tired(11:1091);



% Fatigue Index (Integral)
for i=1:length(jerested)
    index(i)=jetired(i)-jerested(i);
end
Fatigue_Index=sum(index)

Jerest=mean(jerested);
Jetire=mean(jetired);
thrshld=(Jerest+Jetire)/2;

% Determine Number of Delta's
ns=500;
nss=500;
%  ns = nss
```

```matlab
for ii=1:length(jerested)-nss
    rsavg(ii)=Jerest;
    travg(ii)=Jetire;
    thrs(ii)=thrshld;
end
yes=1:length(jerested)-nss;
yes=yes/10;
figure,plot(yes,jerested(nss+1:length(jerested),:),'g',yes,jetired(nss+
1:length(jerested),:),'r',yes,rsavg,'k',yes,travg,'m',yes,thrs,'b');
legend('Rested','Tired','rested mean','tired mean','Threshold')
title('Pilot #2 ~ Steady Flight Fatigue Detector #1')
ylabel('Fatigue Detector Value')
xlabel('Maneuver Time (sec)')
grid on

nn=1;
for fz=1:length(jerested)-nss;



%--------------------------------------------------
%  Inputs
%  1) Mean of last # of samples
k=0;
for i=nn:ns
    k=k+1;
    delrest(k)=jerested(i)-thrshld;
    deltire(k)=jetired(i)-thrshld;
end
delta_mean_re=mean(delrest);
delta_mean_ti=mean(deltire);

%  2) Current Delta
delta_curnt_re=jerested(ns+1)-thrshld;
delta_curnt_ti=jetired(ns+1)-thrshld;


%_____-


%
nn=nn+1;
ns=ns+1;


%_____-




%--------------------------------------------------
% Fuzzification Of Current Input & Mean Input
% Defined Intervals
ln=-.3;
n=-.15;
z=0;
p=.15;
lp=.3;
```

```matlab
% New variable definitions
dmr=delta_mean_re;
dcr=delta_curnt_re;
dmt=delta_mean_ti;
dct=delta_curnt_ti;
%-------------------------------------------------
% Fuzzification of Mean Rested Input
% First Fuzzy Interval
if dmr<=ln
    a=1;
    b=0;
    c=0;
    d=0;
    e=0;

else if dmr<n && dmr>ln
    a=dmr*(1/(ln-n))-1;
    b=dmr*(1/(n-ln))+2;
    c=0;
    d=0;
    e=0;

% Second Fuzzy Interval
    else if dmr>=n && dmr<=z
    b=dmr*(1/(n-z));
    c=dmr*(1/(z-n))+1;
    a=0;
    d=0;
    e=0;
% Third Fuzzy Interval
        else if dmr>z && dmr<p
    c=dmr*(1/(z-p))+1;
    d=dmr*(1/(p-z));
    a=0;
    b=0;
    e=0;

% Fourth Fuzzy Interval
            else if dmr>lp
    e=1;
    d=0;
    a=0;
    b=0;
    c=0;
                else if dmr>=p
    d=dmr*(1/(p-lp))+2;
    e=dmr*(1/(lp-p))-1;
    a=0;
    b=0;
    c=0;
                    end
                end
            end
        end
    end
```

```matlab
    end


%-----------------------------------------------*
% Fuzzification of Rested Current Input
% First Fuzzy Interval
if dcr<=ln
    aa=1;
    bb=0;
    cc=0;
    dd=0;
    ee=0;
else if dcr<n
    aa=dcr*(1/(ln-n))-1;
    bb=dcr*(1/(n-ln))+2;
    cc=0;
    dd=0;
    ee=0;
% Second Fuzzy Interval
    else if dcr>=n && dcr<=z
    bb=dcr*(1/(n-z));
    cc=dcr*(1/(z-n))+1;
    aa=0;
    dd=0;
    ee=0;
% Third Fuzzy Interval
        else if dcr>z && dcr<p
    cc=dcr*(1/(z-p))+1;
    dd=dcr*(1/(p-z));
    aa=0;
    bb=0;
    ee=0;
% Fourth Fuzzy Interval
            else if dcr>lp
    ee=1;
    dd=0;
    aa=0;
    bb=0;
    cc=0;
                else if dcr>=p
    dd=dcr*(1/(p-lp))+2;
    ee=dcr*(1/(lp-p))-1;
    aa=0;
    bb=0;
    cc=0;
                    end
                end
            end
        end
    end
end
%----------------------------------------------------
% Fuzzification of Mean Tired Input
% First Fuzzy Interval
if dmt<=ln
    aaa=1;
```

```matlab
    bbb=0;
    ccc=0;
    ddd=0;
    eee=0;
else if dmt<n
    aaa=dmt*(1/(ln-n))-1;
    bbb=dmt*(1/(n-ln))+2;
    ccc=0;
    ddd=0;
    eee=0;
% Second Fuzzy Interval
    else if dmt>=n && dmt<=z
    bbb=dmt*(1/(n-z));
    ccc=dmt*(1/(z-n))+1;
    aaa=0;
    ddd=0;
    eee=0;
% Third Fuzzy Interval
        else if dmt>z && dmt<p
    ccc=dmt*(1/(z-p))+1;
    ddd=dmt*(1/(p-z));
    aaa=0;
    bbb=0;
    eee=0;
% Fourth Fuzzy Interval
            else if dmt>lp
    eee=1;
    ddd=0;
    aaa=0;
    bbb=0;
    ccc=0;
                else if dmt>=p
    ddd=dmt*(1/(p-lp))+2;
    eee=dmt*(1/(lp-p))-1;
    aaa=0;
    bbb=0;
    ccc=0;
                    end
                end
            end
        end
    end
end


%-----------------------------------------------*
% Fuzzification of Tired Current Input
% First Fuzzy Interval
if dct<=ln
    aaaa=1;
    bbbb=0;
    cccc=0;
    dddd=0;
    eeee=0;
else if dct<n
    aaaa=dct*(1/(ln-n))-1;
```

```matlab
    bbbb=dct*(1/(n-ln))+2;
    cccc=0;
    dddd=0;
    eeee=0;
% Second Fuzzy Interval
    else if dct>=n && dct<=z
    bbbb=dct*(1/(n-z));
    cccc=dct*(1/(z-n))+1;
    aaaa=0;
    dddd=0;
    eeee=0;
% Third Fuzzy Interval
        else if dct>z && dct<p
    cccc=dct*(1/(z-p))+1;
    dddd=dct*(1/(p-z));
    aaaa=0;
    bbbb=0;
    eeee=0;
% Fourth Fuzzy Interval
            else if dct>lp
    eeee=1;
    dddd=0;
    aaaa=0;
    bbbb=0;
    cccc=0;
                else if dct>=p
    dddd=dct*(1/(p-lp))+2;
    eeee=dct*(1/(lp-p))-1;
    aaaa=0;
    bbbb=0;
    cccc=0;
                        end
                    end
                end
            end
        end
end
% end % this ends the loop
% Four fuzzy inputs
% Rested
delmr=[a b c d e]';
delcr=[aa bb cc dd ee];
Fmr=find(delmr);
Fcr=find(delcr);
%Tired
delmt=[aaa bbb ccc ddd eee]';
delct=[aaaa bbbb cccc dddd eeee];
Fmt=find(delmt);
Fct=find(delct);

% Two Fuzzy Commands
Infrmatrix=[-1 -1 -1 -1 -1;
            -1 -1 -1 -1 0;
            -1 0 0 0 1;
            0 1 1 1 1;
            1 1 1 1 1];
% Rested
```

```matlab
FzzyR=delmr*delcr;
FzzycmdR=zeros(5,5);
for iii=1:5
    for jjj=1:5
        FzzycmdR(iii,jjj)=FzzyR(iii,jjj)*Infrmatrix(iii,jjj);
    end
end

% Tired
FzzyT=delmt*delct;
FzzycmdT=zeros(5,5);
for iii=1:5
    for jjj=1:5
        FzzycmdT(iii,jjj)=FzzyT(iii,jjj)*Infrmatrix(iii,jjj);
    end
end

% FzzyCmd;
% %--------------------------------------------------
% % Deffuzification
% % Definition of intervals for membership function
% Tired Range & Area
Tlb=.25;
Tub=1.75;
TA=(Tub-Tlb)/2;
% Inconclusize Range & Area
Iub=.5;
Ilb=-.5;
IA=(Iub-Ilb)/2;
% Rested Range & Area
Rub=-.25;
Rlb=-1.75;
RA=(Rub-Rlb)/2;

% Area Matrix
AM=[RA,RA,RA,RA,RA;
    RA,RA,RA,RA,IA;
    RA,IA,IA,IA,TA;
    IA,TA,TA,TA,TA;
    TA,TA,TA,TA,TA];
%--------------------------------------------------
% Center of Sums Method w/ Scaled Areas
% Finding the top part of Crisp Command
mmm=0;
for i=1:length(AM)
    for ii=1:length(AM)
        mmm=1+mmm;
        utopr(mmm)=FzzycmdR(ii,i)*AM(ii,i);
        utopt(mmm)=FzzycmdT(ii,i)*AM(ii,i);
    end
end

u_topr=sum(utopr);
u_topt=sum(utopt);

rbot=find(utopr);
```

```matlab
tbot=find(utopt);

u_botr=length(rbot)*RA;
u_bott=length(tbot)*TA;

Crspcmdr(fz)=(u_topr/u_botr+1)/2;
Crspcmdt(fz)=(u_topt/u_bott+1)/2;

end
% end of loop
time=1:fz;
time=time/10;
figure,plot(time,Crspcmdr,'g',time,Crspcmdt,'r')
axis([0 fz/10 -.2 1.2])
legend('Rested','Tired')
title('Fuzzy Logic Detection Scheme - Steady Flight - Pilot #2')
ylabel('Fuzzy Output ~ % Tired')
xlabel('Maneuver Time (sec)')
grid on


% Generalized Output
% Rested Data
GCrspR=zeros(1,fz);
GCrspT=zeros(1,fz);
for i=1:fz
if Crspcmdr(i)>.6
    GCrspR(1,i)=1;
else if Crspcmdr(i)>=.4 & Crspcmdr(i)<=.6
        GCrspR(1,i)=.5;
    else if Crspcmdr(i)<.4
            GCrspR(1,i)=0;
        end
    end
end
% Tired Data
if Crspcmdt(i)>.6
    GCrspT(1,i)=1;
else if Crspcmdt(i)>=.4 & Crspcmdt(i)<=.6
        GCrspT(1,i)=.5;
    else if Crspcmdt(i)<.4
            GCrspT(1,i)=0;
        end
    end
end
end
figure,plot(time,GCrspR,'g',time,GCrspT,'r')
axis([0 fz/10 -.2 1.2])
legend('Rested Pilot','Tired Pilot')
ylabel('% Tired')
xlabel('Maneuver Time (sec)')
```