TESTING OF A FLIGHT ENVELOPE PROTECTION SYSTEM FOR FLY-BY-WIRE AERIAL VEHICLES

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ABSTRACT

TESTING OF A FLIGHT ENVELOPE PROTECTION SYSTEM FOR FLY-BY-WIRE AERIAL VEHICLES

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Aircraft should remain in their flight envelope during their operation. Monitoring these limits while coping with other mission related tasks increase the pilot workload substantially. In this thesis, envelope protection methods and tactile cues are investigated for pilot workload reduction and their effectiveness compared to both conventional methods and each other. For this purpose, a simulator environment centered around an active inceptor is established such that both rotary and fixed-wing configurations are possible. With the Direct Adaptive Limit Margin Estimation method envelope boundaries are estimated. Different tactile cueing methods are developed. Via the active inceptor, cueing of the estimated limits with developed methods are tested in both piloted and pilotless simulations. Pilot reviews for tested cueing methods are scaled with the NASA-TLX method and compared with each other.

Keywords: Tactile Cue, Haptic Cues, Active Stick, Envelope Protection, Carefree Maneuvering

ÖZ

FLY-BY-WİRE HAVA ARAÇLARI İÇİN UÇUŞ ZARFI KORUMA SİSTEMİNİN TEST EDİLMESİ

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Hava araçları uçuşları sırasında belli bir uçuş zarfının içinde kalmalılardır. Uçuş zarfı limitlerini takip ederken bir yandan görevleriyle ilgili işlerle uğraşmak, pilotların iş yükünü hayli artırmaktadır. Bu tezde, uçuş zarfı koruma sistemleri ve dokunsal geri bildirim uyarıları ile pilot iş yükünü azaltmaya çalışan yöntemler ve bu yöntemlerin hem geleneksel yöntemlere hem de birbirlerine göre etkinlikleri kıyaslanmıştır. Bu amaçla aktif bir pilot kontrolü etrafında, hem döner kanat hem de sabit kanat platformlar için kullanılabilen bir simülatör kurulmuştur. Doğrudan Adaptif Limit Marjin Tahmini yöntemi ile uçuş zarfı limitleri hesaplanmaktadır. Farklı dokunsal geri bildirim yöntemleri geliştirilmiştir. Aktif pilot kontrolü üzerinden, tespit edilen limitlerin geliştirilen haptik geri bildirim yöntemleri ile pilotlu ve pilotsuz simülasyonlar ile testleri yapılmıştır. Pilot yorumları NASA-TLX yöntemi ile değerlendirilmiş çıkan sonuçlar ile dokunsal geri bildirim yöntemlerin kıyaslanması yapılmıştır.

Anahtar Kelimeler: Dokunsal Geri Bildirim, Aktif Kontroller, Uçuş Zarfı Koruma

To my family...

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LIST OF ABBREVIATIONS

FBW	Fly-by-Wire
CFMS	Carefree Maneuvering Systems
MFD	Multi Functional Displays
HUD	Heads-up Display
HMD	Helmet Mounted Display
AFCS	Automatic Flight Control System
SAS	Stability Augmentation System
RPM	Revolutions per second
PNN	Polynomial Neural Networks
HQRs	Handling Qualities Ratings
TLX	Task Load Index
RTLX	Raw TLX
DALME	Direct Limit Margin Estimation
SHLNN	Single Hidden Layer Neural Network
SMC	Simulation controller
MFD	Multi Function Display

CHAPTER 1

INTRODUCTION

1.1 Motivation and Problem Definition

Aircraft have flight envelopes which their boundaries should not be passed. These boundaries are dependent generally to aerodynamic, structural, control, operational and power limits. Pilots constantly monitor these parameters from visual cues to avoid limit exceedance. Although this provides safety, it increases the pilot workload. To assist the pilot with this task, Envelope Protection Systems (EPS) came in to sight. These systems aim to cue the pilot effectively to avoid envelope boundaries, improve safety and handling qualities.

First generations of fly-by-wire (FBW) systems, used passive sticks which does not move or move with a preset stiffness. With the introduction of active inceptors, the force and moments on the control surfaces started to mimicked. This allowed the pilot to get a better feel of what is the aircraft doing. This also opened research areas for new cueing methods. As the feel characteristics of the active inceptor can be changed, feedback can be given to the pilot over the inceptor. These cues are called tactile cues.

1.2 Literature Survey

The purpose of Envelope Protection Systems are not to only avoid exceeding flight envelope limits but also to enable effective maneuvering along the boundaries. This is why Envelope Protection Systems are also known as Carefree Maneuvering Systems (CFMS) [1]. With these systems, the allowable safe operational envelope of the aircraft can be increased as the pilot workload is not as high compared to aircraft without CFMS.

A simple way to cue the pilots are usage of visual or aural cues. Warnings can be displayed on Multi Functional Displays (MFDs) or Heads-up Display (HUD) for visuals. Also aural cues can be given as the aircraft gets closer to its limits. These type of cues can be set to initiate at a predetermined conservative limit to warn the pilot ahead of approaching limit boundaries. Such cues with conservative limits are found in the RAH-66 helicopter [2]. Where cues for load factor, engine torque and main rotor shaft bending limits are cued through the pilot headset and Helmet Mounted Display (HMD). Such cues can be too conservative for some flight conditions while can be not sufficient enough in cases of fast transient dynamics. To correctly select these limits, flight tests and tuning with pilots are required.

If an Automatic Flight Control System (AFCS) or Stability Augmentation System (SAS) is available in the aircraft, pilot inputs can be manipulated by changing controller gains as limits gets close. Such a method can be found in the Eurofighter where angle of attack and load factor boundaries are avoided by the manipulation of pilot inputs through the flight control system [3]. A similar and simpler system can be found in the Airbus A319/320 aircraft for angle of attack and load factor protection [4]. These systems presented in [3, 4] do not allow the pilot to override the protection system. In such cases extra care might be needed in the design as handling qualities of aircraft can be degraded by changing controller gains.

In FBW control systems, the pilot controls are not mechanically connected to control surfaces. In these systems passive or active inceptors are used for controls. With passive inceptors the pilot cannot feel the aerodynamic forces on the control surfaces, instead only the desired inputs are transmitted to actuators from the flight control system. As opposed to passive inceptors, the data flow is both ways on active inceptors. In such, the pilot can get feedback from the inceptor through the change of force characteristics via electrical motors. These can be used to mimic aerodynamic forces on the control surfaces. Also active inceptors can be used to give cues by limiting the available travel, changing the required force to move the stick, shake the stick or in different combinations of these. Such cues are called tactile cues because the pilot is cued via the sense of touch.

Tactile cues are shown to be an more effective option to visual and aural cueing in studies [5, 6, 7, 8] and it is also demonstrated that tactile cueing effectiveness can be increased if the cueing is provided ahead of actual limit exceedance. To achieve this a future state's, of the aircraft, proximity to envelope limits and its control axes mapping is required. In envelope protection, the proximity of a future state and envelope limit is called limit margin and the translated limit margin on the control axis is called control margin. These margins are important for flight envelope protection and prediction of these margins are known as limit detection [1].

After limit detection, the estimated margins are used to cue the pilot about approaching envelope boundaries. This is known as limit avoidance and can be achieved through control limits [1]. Control limits are the locations of pilot cue initiation on the control axis of the inceptor. Limit and control margin estimation is essential for envelope protection. By using control margins and active sticks in unison effective limit protection can be achieved.

In studies [2, 3, 4] conservative limit detection is used for envelope protection. These methods do not rely on lead time estimations meaning, they do not use a future state estimation and its proximity to limits for cueing the pilot. However studies [5, 6, 7, 8] make use of future state estimates for cueing. Early studies for the usage of future state estimates begin with [9] where the current RPM of the main rotor and collective input are used to calculate the RPM value at the next time step. This prediction method is limited to one step ahead.

Active and passive inceptors are compared in [5]. Differences between active and conventional inceptors are given under Chapter 3, Active Inceptor subsection. [5] uses polynomical neural networks (PNN) for lead time estimation. PNNs are trained offline and are used to make online predictions on a fixed time horizon. In [10], it is shown that neural network's prediction time step often limit fixed time horizon predictions.

By using the maneuvering steady state of an aircraft, future states of the aircraft can be estimated. The maneuvering of steady state is called dynamic trim. Where fast states of the aircraft such as angle-of-attack and load factor are on equilibrium and slow states can still be changing. This is first used in [6] for envelope protection.

Allowable control travels of a tilt-wing aircraft are estimated.

In [11], iterations are done for online parameter estimations. With limited information of the plant, limit and control margin estimation is done. [12] and [13] introduce concurrent learning. [1] estimates limit parameters without online iterations using previous concurrent learning augmentation with a method called Direct Adaptive Limit Margin Estimation.

While comparing active and conventional inceptors, [5] uses Handling Qualities Ratings (HQRs). Nasa Task Load Index (TLX) [14] is a tool used for workload assessment. [15] shows the development of the NASA TLX method. With [16], dropping the pairwise comparisons of elements in the TLX method, called Raw TLX (RTLX), is shown to be a sufficient and in [17] it is shown that RLTX might increase experimental validity. In [18] and [19] workload of active inceptors and tactile cues are investigated. In these studies the NASA TLX method is used in both full and raw versions.

1.3 Contributions and Novelties

Our contributions are as follows:

- A modular simulator environment for envelope protection and tactile cueing development and testing is established.

- Previously developed Direct Limit Margin Estimation algorithm is coupled with the active inceptor to work cooperatively for real flight scenarios.

- Different tactile cueing methods for the active stick is proposed, problems and solutions encountered while their applications are demonstrated.

- Piloted tests are made, workloads of different cueing methods are rated with NASA-TLX method and compared with each other for further development.

1.4 The Outline of the Thesis

In chapter 2 , the methods used in this study is given. For limit estimation, the implementation of Direct Adaptive Limit Margin Estimation method and its adaptive element, Single Hidden Layer Neural Network is given. Afterwards, the established simulation environment and its capabilities are expressed. The core of the simulator environment, the active inceptor, and developed tactile cueing methods are given in the following subsection. The chapter is finalized by discussing the NASA-TLX method and its usage with piloted tests.

Simulation and results are given in chapter 3 . Firstly the limit parameters and their estimation with the previously mentioned methods are given. Followed by pilotless simulations for different test scenarios and their results are discussed. Piloted simulations and results of NASA-TLX are given at the end of this chapter.

With chapter 4 , conclusion of the work done and future work suggestions are given. The statistical data collected from pilots with the NASA-TLX rating questionnaires in there original form are given in the Appendix.

CHAPTER 2

METHODOLOGY

Tactile cues can be initiated when In this study, DALME is used to estimate limits. SHLNN is used for adaptive element. Different tactile cues from active stick and flights with pilots for tests.

2.1 Direct Adaptive Limit Margin Estimation

The method described in [13] is used for limit margin estimation. The summation of an approximate inverse model and adaptive element is used as the estimation of the limit parameter. Then sensitivity, S, of the limit parameter to the input is calculated. Which is used to calculate the linear relation between the limit and control margin. The limit parameter y_p can be written as follows:

$$y_p = h(\mathbf{x}_f, \mathbf{x}_s).y_p \in \Re, x_f \in \Re^l, x_s \in \Re^{n-l} \tag{21}$$

Where x_f and x_s are the fast and slow states of the plant, respectively. h is assumed to be invertable in [20], $x_f = h^{-1}(y_p, \mathbf{x_s})$. y_p can then be expressed as the summation of approximate model inverse, $\hat{g}_n$, and modeling error, ξ. Where, $u_e \in \Re$ is the control input.

$$y_p = \hat{g}_n^{-1}(\mathbf{x}_s, \dot{\mathbf{y}}_p, u_e) + \xi. \tag{22}$$

As explained by [13] and [20] $\dot{\mathbf{y}}_p = [y_p^{(1)}, y_p^{(2)}, ..., y_p^{(n)}]^T \in \Re^n$, vector of derivatives, can be estimated in the delayed time step. With and adaptive element, $delta$, y_p can be estimated:

$$\hat{y}_p = \hat{g}_n^{-1}(\mathbf{x}_s, \dot{\mathbf{y}}_p, u_e) + \Delta(\mathbf{x}_s, \dot{\mathbf{y}}_p, u_e). \tag{23}$$

By inserting zeros to derivative terms in Eq.(23) the steady state value of limit parameter, y_p, is found:

$$\hat{y}_{p_{ss}} = \hat{g}_n^{-1}(\mathbf{x}_s, 0, u_e) + \Delta(\mathbf{x}_s, 0, u_e) + e_d. \tag{24}$$

As shown in [13, 20], control sensitivities are used for control margin calculations. The steady state limit margin, $\hat{y}_{p_{margss}}$, is:

$$\hat{y}_{p_{margss}} = y_{p_{lim}} - \hat{y}_{p_{ss}}. \tag{25}$$

Where $y_{p_{lim}}$ is a known limit boundary. Sensitivity, $S \in \Re$, to the effective control input becomes:

$$\boldsymbol{S} = \frac{\partial \hat{y}_{p_{ss}}}{\partial u_e} = \frac{\partial(\hat{\boldsymbol{h}}_1^{-1}(\boldsymbol{x}_s, 0, \boldsymbol{u}_e) + \boldsymbol{\Delta}(\boldsymbol{x}_s, 0, \boldsymbol{u}_e))}{\partial u_e}. \tag{26}$$

The linear relation between the limit and control margin can be formed as:

$$\hat{y}_{p_{margss}} = S\hat{u}_{\boldsymbol{e}_{marg}}. \tag{27}$$

If $\hat{u}_{\boldsymbol{e}_{marg}} = \hat{u}_{e_{lim}} - u_e$ then:

$$\hat{u}_{e_{lim}} = \frac{1}{S}\hat{y}_{p_{margss}} + \boldsymbol{u}_e \tag{28}$$

Eq.(28) can be modified with the instant limit margin, $y_{p_{marg}}$, if the limit parameters reach the limits during transient response:

$$\boldsymbol{u}_{e_{lim}} = min\left(\left|\frac{1}{S}y_{p_{marg}}\right|, \left|\frac{1}{S}y_{p_{margss}}\right|\right) + \boldsymbol{u}_e \tag{29}$$

2.2 Single Hidden Layer Neural Network with Concurrent Learning

With SHLNN, model uncertainity, ξ, can be nonlinearly parametrized:

$$\xi(\bar{x}) = W^{*T}\sigma(V^{*}T\bar{x}) + \epsilon \tag{210}$$

Here; the input vector is $\bar{x} = [x_s(t), \bar{\partial}(y_p), u_e]^T \in \Re^{r+1}$ and the vector function is $\sigma(z) = [b_w, \sigma_1(z_1), \sigma_2(z_2), \ ..., \ \sigma_m(z_m)]$, where $i = 1, 2, ..., m$ and $z = V^T\bar{x}$. $W^* \in \Re^{(m+1)\times l}$ and $V^* \in \Re^{(r+1)\times m}$ are the optimal synaptic weights that connect the hidden layer to output layer and the input layer to hidden layer, respectively. The sigmoidal activation functions are given by:

$$\sigma_i(z_i) = \frac{1}{1 + e^{-a_i z_i}} \tag{211}$$

Again recording the approximation error, e, and the basis,$\bar{x}$, in history stack matrix and using the assumptions in [21] the weight update law becomes:

$$\dot{W}(t) = \Gamma_W((\sigma(V^T\bar{x})-\sigma'(V^T\bar{x})V^T\bar{x})e^T+W_c\sum_{j=1}^{p}(\sigma(V^T\bar{x}_j)-\sigma'(V^T\bar{x}_j)V^T\bar{x}_j){e_j}^T) \tag{212}$$

$$\dot{V}(t) = \Gamma_V\bar{x}e^TW^T\sigma'(V^T\bar{x}) + V_c\sum_{j=1}^{p}\bar{x}_j{e_j}^TW^T\sigma'(V^T\bar{x}_j) \tag{213}$$

where;

$$W_c = I - \frac{(\sigma(V^T\bar{x})-\sigma'(V^T\bar{x})V^T\bar{x})(\sigma(V^T\bar{x})-\sigma'(V^T\bar{x})V^T\bar{x})^T}{(\sigma(V^T\bar{x})-\sigma'(V^T\bar{x})V^T\bar{x})^T(\sigma(V^T\bar{x})-\sigma'(V^T\bar{x})V^T\bar{x})} \tag{214}$$

$$V_c = I - \frac{\bar{x}\bar{x}^T}{\bar{x}^T\bar{x}} \tag{215}$$

A proof of boundedness for the above weight update law can be found in [21].

2.3 Simulation Environment

The simulator environment consists of an active inceptor, Flight Link Advanced Helicopter Package [22], Saitek pilot controllers [23] and two desktop computers (Figure 2.1). Computers run on Windows operating systems with Nvidia GTX770 graphic cards (Two in Computer 2). Flight Link Advanced Helicopter Package consists of a cyclic, collective, pedals and a pilot seat. Saitek pilot controllers comprise of a stick and throttle. The throttle controller from Saitek and the collective from Flight Link are used interchangeably for different flight models, namely for fixed-wing and rotary-wing models. The active inceptor is used as a side stick for both control stick and cyclic purposes.

2.3.1 Simulation Setup

The simulator is set for two main configurations. One configuration is for rotary-wing while the other is for fixed-wing simulations. By simply swapping the collective and throttle the aircraft configuration of the simulator setup can be changed. This makes

Figure 2.1: Simulator Environment.

a time and cost effective simulator environment for different platforms as most of the parts are used mutually between configurations.

2.3.1.1 Rotary-Wing Configuration

The rotary-wing configuration makes use of both computers. The two computers are connected to each other with TCP/IP connections. Flight Link controllers are connected to Computer 2 while Saitek controllers are connected to Computer 1, both with USB connection. The active inceptor is connected to Computer 1 through UDP. Computer 1 runs the simulation controller (SMC), Simulink model and multi-function display (MFD). On Computer 2, the flight model and X-Plane runs. SMC controls the simulator by initialize and start/stop options. It also shows if the connections between hardware and software components established correctly. With the input from pilot controls, the flight model calculates the aircraft states and then sends them to X-Plane for visualization and Computer 1. Through Computer 1 the MFD and Simulink model is fed. The flight model gets the Flight Link inputs over Computer 2 while pilot inputs from the active inceptor is from the Simulink model. Flight Link cyclic, active inceptor and active inceptor can all be used and each case all of them can override each other. The configuration used here is Stirling active stick and Flight Link pedals and collective. The Simulink model allows running the envelope protection algorithms and feeding the outcomes to the active inceptor and flight model through S-functions. One S-function is for the flight model so it can run simultaneously with the flight model on Computer 2. The other S- function is for communicating with the active inceptor. The flow chart of this setup can be seen in Figure 2.2.

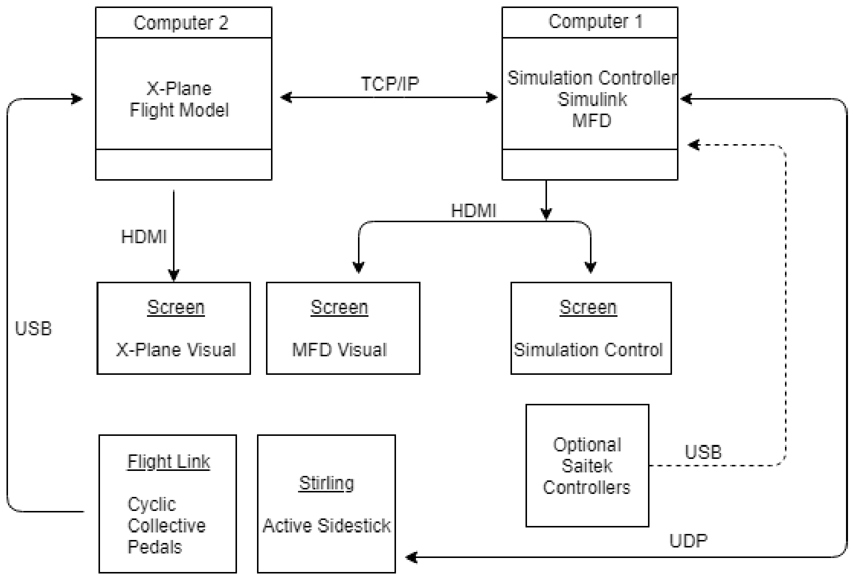


Figure 2.2: Rotor-Wing Simulator Flow Chart.

2.3.1.2 Fixed-Wing Configuration

For this configuration, Flight Gear is used for visuals and flight model runs on directly on simulink. So, this configuration is able to use only one computer, Computer 1. The connection of Saitek controllers and active inceptor remains the same as the other configuration. As only Computer 1 is used in the fixed-wing setup, Flight Link controllers are connected to it, instead of Computer 2. The flight model runs on Simulink and aircraft states are sent to Flight Gear for visualization. Also these states are fed back to the Simulink model which runs the envelope protection algorithm and active stick controller. The desired outcomes of the active stick controller sends the necessary information to the inceptor through a S-function. As the rotary-wing case; the cyclic, active inceptor and Saitek stick can override each other. For this configuration the main controls are set as, active inceptor, Flight Link pedals and Saitek throttle. Flow chart of this configuration is given in Figure 2.3

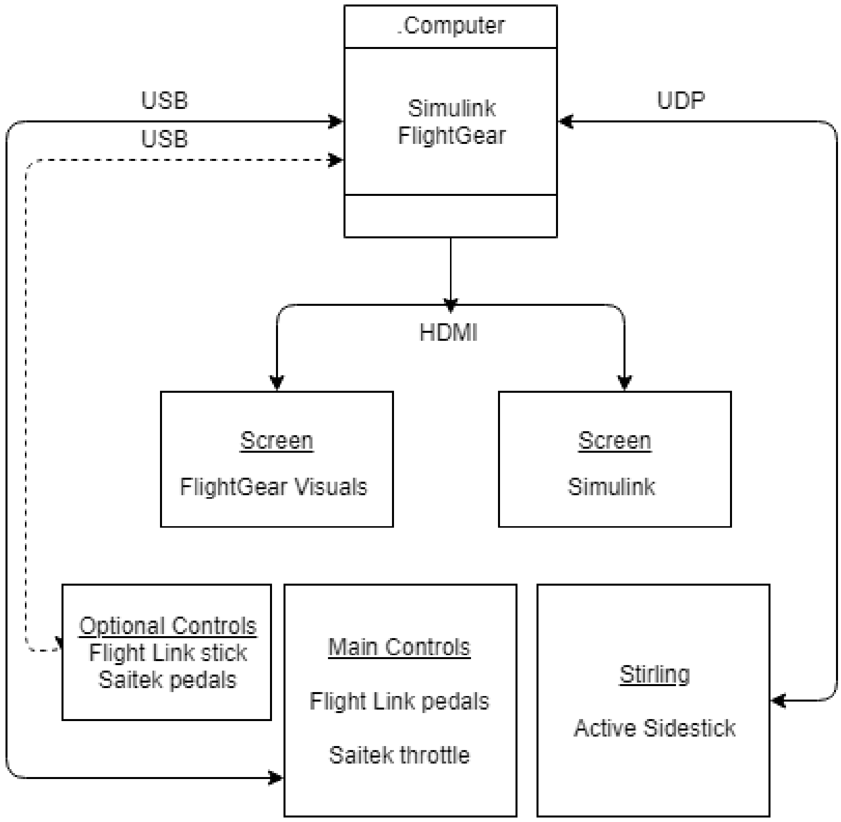


Figure 2.3: Fixed-Wing simulator flow chart.

2.3.2 Active Inceptor

Active inceptors are pilot controls which replace the springs and dampers of traditional control systems. The stiffness and dampening are given by programmable electric motors. Besides giving the passive feel of springs and dampers these electric motors provide the ability to change the characteristics and feel of stick. The ability to actively change the force characteristics of the stick brings out the main difference between active and passive sticks. That is, in active inceptors the data flow is on both directions compared to passive sticks where data flow is only from pilot to stick (Figure 2.4). This property can be used in various ways. The following list can be given as examples for different usages:

- Mimicking mechanical connections between control surfaces and the stick so that the pilot can feel hinge moments
- Coupling two sticks without mechanical linkage to save weight and give feedback to pilots about each others inputs
- Simulating mechanical jams or control surface loss etc. for training purposes
- Giving tactile cue feedbacks for limit avoidance with reduced pilot workload

The last item given above, is the main concern of this thesis. The active inceptor selected for these studies is the Stirling Dynamics Next Generation Inceptor 2.5. It has configurable feel, force and dynamic characteristics. The inceptor and computer connection is half duplex and made over UDP. With a maximum of 30 Hz, the inceptor continuosly gives information about its current state. Each time a change in the force profile of the inceptor is needed, an array of force values and corresponding stick angles are sent to the inceptor. With this information, the active stick generates a new force profile with linear interpolation between the data points it receives. By continuously updating the force profile of the inceptor, various tactile cues can be generated.

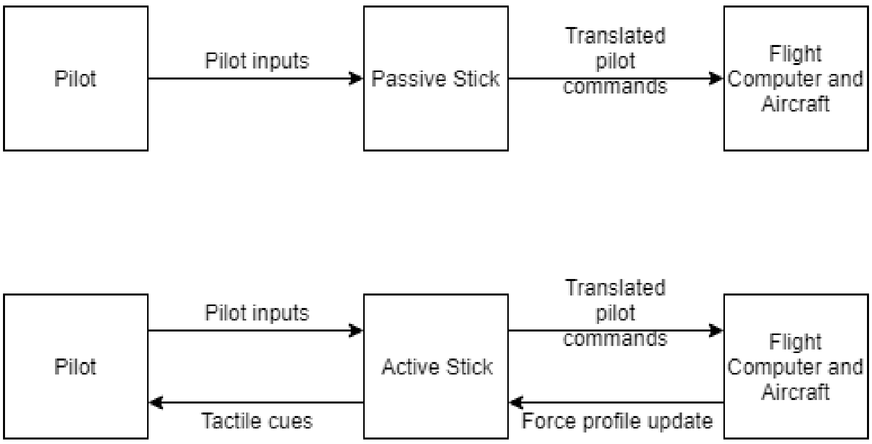


Figure 2.4: Data flow comparison of active and passive inceptors.

The basic, passive, settings of the inceptor can be seen in Figure 2.6. A 3 Newton breakout is set for both control axis. The pitch axis is limited to +-24 degrees while the roll axis is limited to +-20 degrees. The force gradient on both axis are characterized

Figure 2.5: Stirling Dynamics Next Generation Inceptor.

by the slope angle. For pitch and roll axis the slope angle is set as 45 and 40 degrees respectively but, can be changed by pilot preferences. The tactile cues used in this study are tailored around the settings of the passive mode, with an exception for variable gradient cues.

In the following subsections, different tactile cue profiles that are used in this work are given.

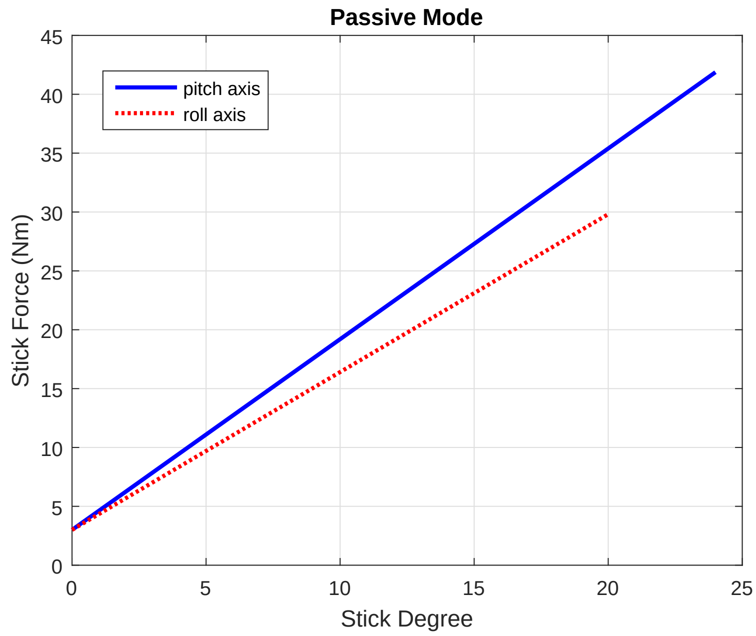


Figure 2.6: Passive mode force profile.

2.3.2.1 Hard Stop

The hard stop method cues the pilot by preventing limit exceedance. On the limit, the inceptor blocks any further movement in the limit exceeding direction. So even if the pilot wanted to pass the limit, it can not be done with this method. As seen from Figure 2.7, the limit initiation point moves with the control margin, thus control limit. If limit onset is estimated in any point over the control axis, the cueing is initiated. Until a limit exceedance is predicted, the stick acts with a predefined passive force gradient. This is also the case for no limit exceedance.

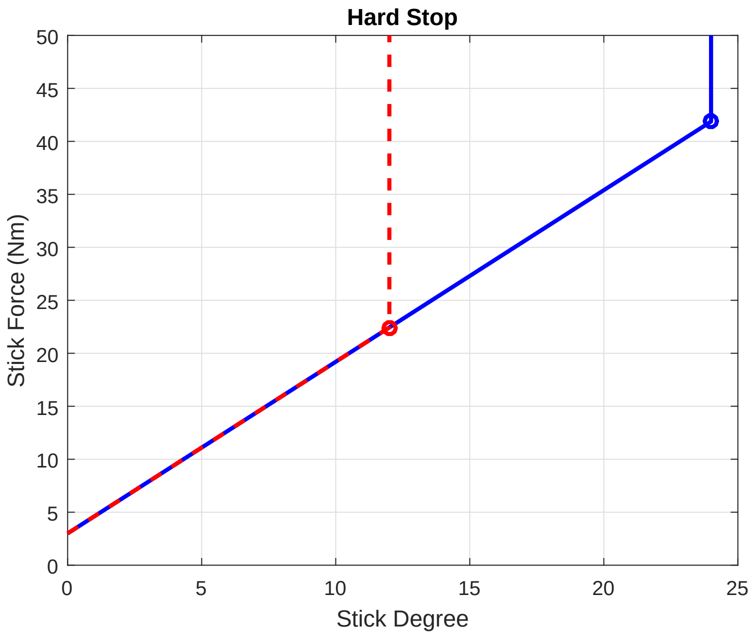


Figure 2.7: Hard Stop method.

2.3.2.2 Soft Stop

Similar to the hard stop, initiation of soft stop moves with available control limit. The difference lies in that the pilot can surpass the limit if desired. At limit, the inceptor changes the force gradient steeply over a small stick angle deflection and then continuous with the same force gradient. From the pilot, this is seen as a shift of required force to move the inceptor, which effectively stops the pilot from exceeding the limit undesirably. If desired, the pilot can pass the limit by applying enough force to the stick. The reason the jump in force is given over a small stick angle range, 0.1 degree in this case, is to give the pilot the ability to fine tune their inputs on the limit boundary. If the force jump is too sudden, the feel becomes abrupt and obstructs the pilot from giving fine inputs. The force profile can be seen in Figure 2.8

2.3.2.3 Shaker

The shaker cueing method uses the same force profile with the passive mode. The only difference is that at and beyond the control limit of the inceptor, the stick starts to shake with a predefined amplitude and frequency. This behavior is shown in Figure

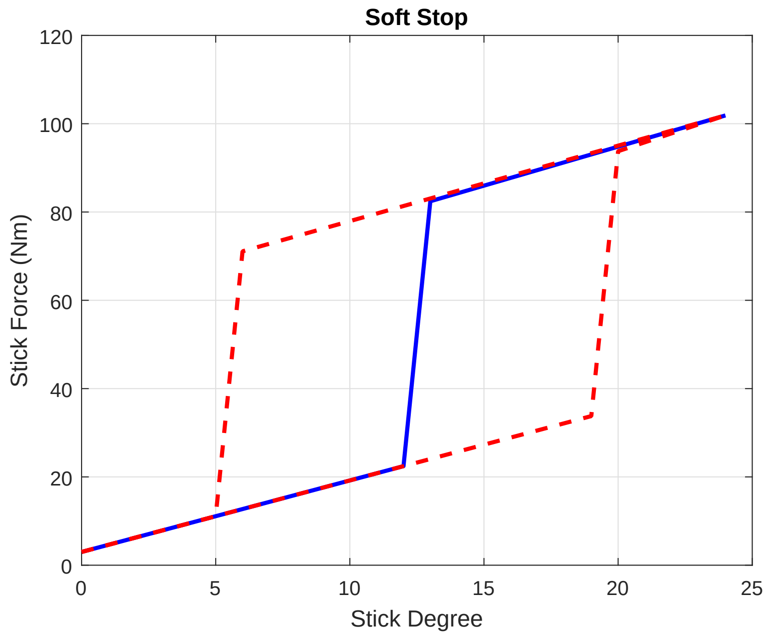


Figure 2.8: Soft Stop method.

2.9. As a default 20Hz and 20 birim amplitude? is set for the shaker but this can changed if the pilot desires to. As the stick does not have a stop in this mode, the pilot can freely move the inceptor as desired.

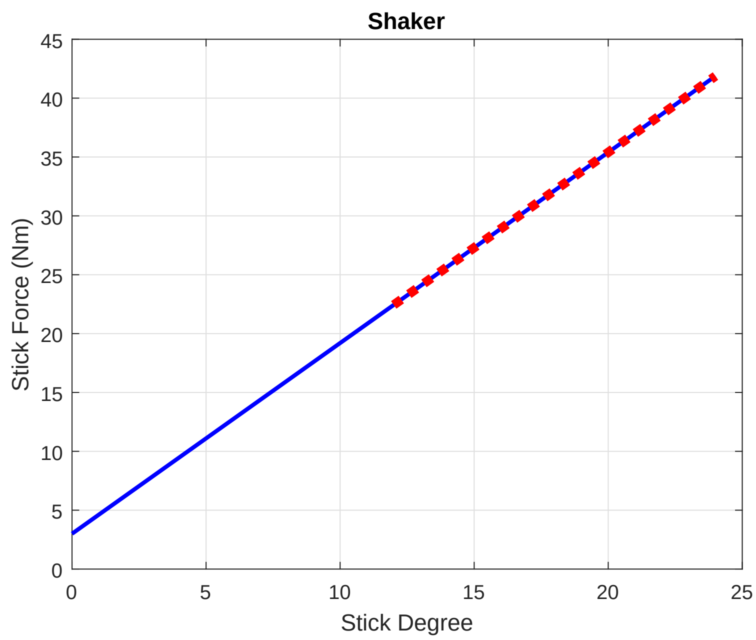


Figure 2.9: Shaker method.

2.3.2.4 Hard Stop with Shaker

This method combines the previously mentioned "hard stop" and "shaker" cues, Figure 2.10. As the pilot commands the aircraft towards envelope boundaries, the inceptor starts to shake on an initial limit point. This point is determined according to the actual limit and both limit points move together with respect to estimated control limits. If after the shaker initiation the pilot continuous towards the limit boundary, the hard stop cue is given at limiting point. The pilot cannot pass this stop even if desired. This cue is useful to give the pilot feedback before the hard stop initiation. So, the pilot would not be surprised with a sudden hard stop and can arrange their input smoothly, without disruption, towards the limit boundary.

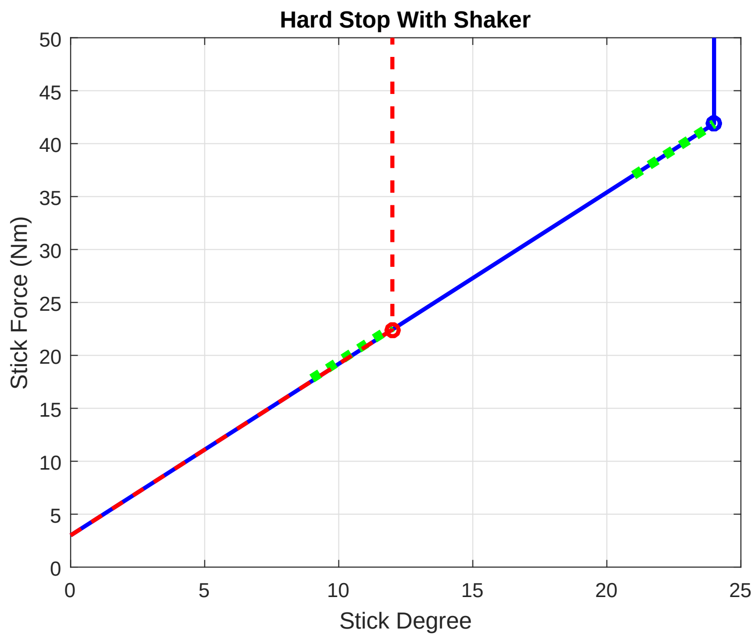


Figure 2.10: Hard Stop with Shaker method.

2.3.2.5 Soft Stop with Shaker

Similar to "Hard Stop with Shaker" this method too combines different cueing methods. In this case, the "soft stop" and "shaker". In this case, the first initiated cue at the initial limit point is the soft stop. The shaker activates when the aircraft is just about to pass the limits. Again, the initial limit point and the actual limit point on the inceptor axis move together with the estimated control limits. With this method, the pilot is stopped when the aircraft gets within a safe margin of the limit. The pilot can intentionally pass this point by giving enough extra force to overcome the stop. After the aircraft passes this point an the pilot continuous to maneuver towards envelope boundaries, the shaker initiates onset of these boundaries. Still, the pilot can pass this point too as there is no hard stop. The force profile is shown in Figure 2.11.

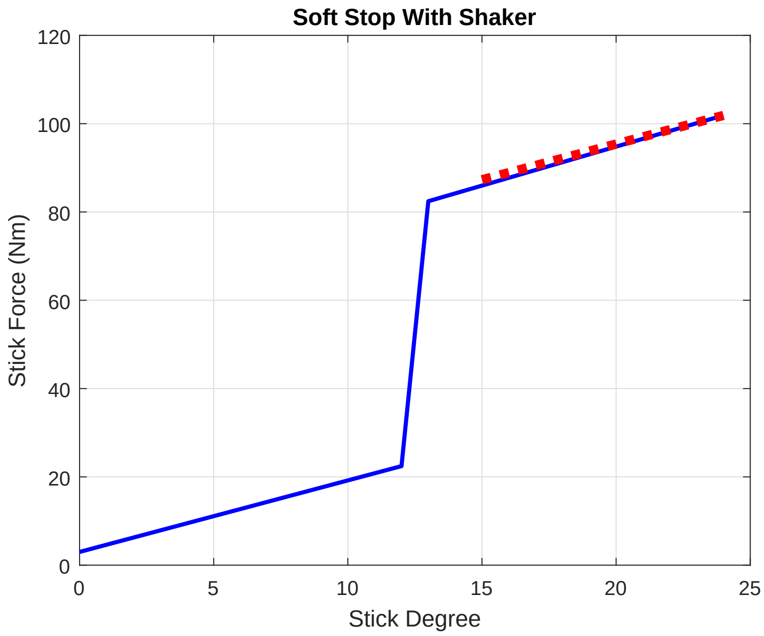


Figure 2.11: Soft Stop with Shaker method.

2.3.2.6 Variable Gradient Hard Stop

The "Variable Gradient Hard Stop" cue force profile can be seen in Figure 2.12. As the name indicates, the force gradient of the inceptor continuously changes according to control margins. The degree component of the breakpoints move with the control limit while the corresponding force value for those breakpoints do not change. This results in a constantly changing slope with respective to control limits. The required force to change the stick angle changes steeply as the pilots fly towards envelope limits. Ultimately, the stick gets to its heaviest state at the control limit so that the pilot cannot exceed aircraft limits.

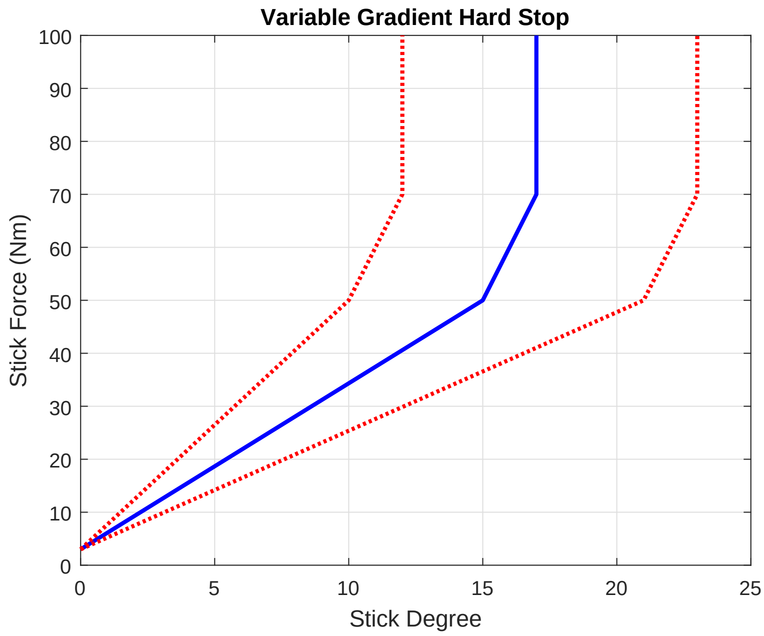


Figure 2.12: Variable Gradient Hard Stop method.

2.3.2.7 Variable Gradient Soft Stop

Similar to the previous method, the stick feel gets heavier as the pilot gets close to aircraft limits. But in this method, the force requirements are set so that the pilot can overcome the required force at the limit and get into a zone where the stick acts with a constant low gradient profile. This enables a relaxed control over the stick beyond limits.

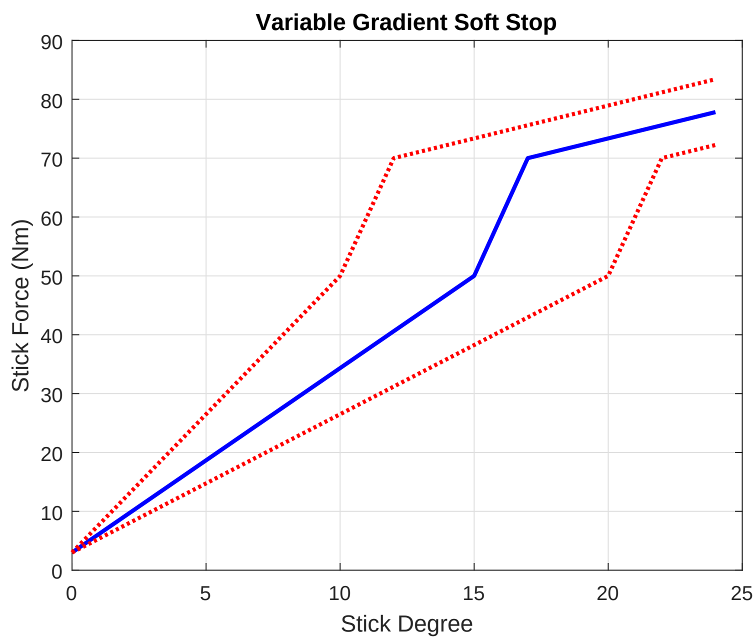


Figure 2.13: Variable Gradient Soft Stop method.

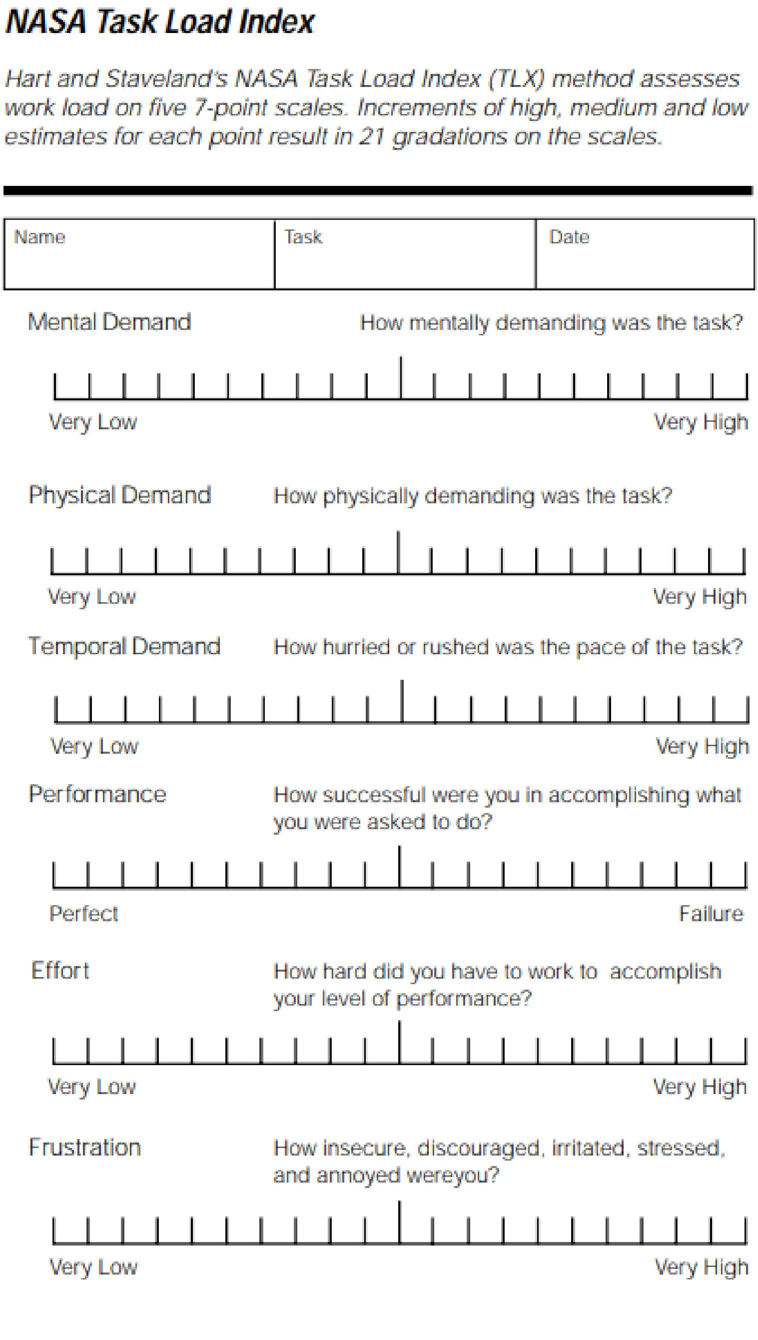
2.4 NASA Task Load Index

As discussed in previous sections, carefree maneuvering systems and tactile cues aim to reduce pilot workload. To evaluate the effectiveness of used systems and developed cues, the pilot workload should be assessed. To measure this subjective matter, the NASA-Task Load Index (NASA-TLX) is selected as it is a widely accepted quantitative method and used as a benchmark against other measures, theories and models efficacy are judged [16]. The NASA-TLX method describes the workload as a hypothetical construct that represents the cost incurred by human operator to achieve a particular level of performance and proposes a multidimensional technique where specific sources of workload relevant to a given task can be identified and considered in computing a global workload rating [15].

NASA-TLX consists of two parts. The first part is a rating scale that defines 7 dimensions. The second part is a weighting operation to find the contributions of dimensions given in the first part. These scales can be seen in Figure 2.14 The pilot gives a score for each rating by selecting the increments on each corresponding scale. After that weights the dimensions by selecting the dimension that contributed more to workload when compared in pairs. The instructions of the method are given in [14]

In this study, a common modification to NASA-TLX ,the "Raw TLX (RTLX)" method, is used. RTLX refers to dropping the pairwise weighting process of the method [16]. This is decided as [17] shows that the shortened method might increase experimental validity. RTLX simply gives an estimate of the overall workload and also gives the ability to compare each rated dimension on its own for different tactile cueing methods presented in this study. The descriptions for each dimension are given in [14] are presented below.

- Mental Demand: How much mental and perceptual activity was required (eg. thinking, deciding, calculating, remembering, looking, searching etc)? Was the task easy or demanding, simple or complex, exacting or forgiving?
- Physical Demand: How much physical activity was required (e.g. pushing, pulling, turning, controlling, activating. etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
- Temporal Demand: How much time pressure did you feel due to the rate or pace at which the tasks ortask elements occured? Was the pace slow and leisurely or rapid and frantic?
- Performance: How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?
- Effort: How hard did you have to work (mentally and physically) to accomplish your level of performance?
- Frustration Level: How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?



NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name	Task	Date

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

Figure 2.14: NASA-TLX workload rating dimensions.

CHAPTER 3

SIMULATION AND RESULTS

For the simulation and tests, load factor and angle of attack are selected as limit parameters. This chapter begins with how the selected parameters are treated as critical limit parameters and then estimated. After, simulation results for different test scenarios are given for hard and soft stop cueing methods. The piloted tests and NASA-TLX workload results are shown at the end of this chapter.

3.0.1 Load Factor as the Critical Limit Parameter

Consider the following simulation block diagram in Figure 3.1, where both the longitudinal channel and the lateral is made open loop. In this setup load factor is

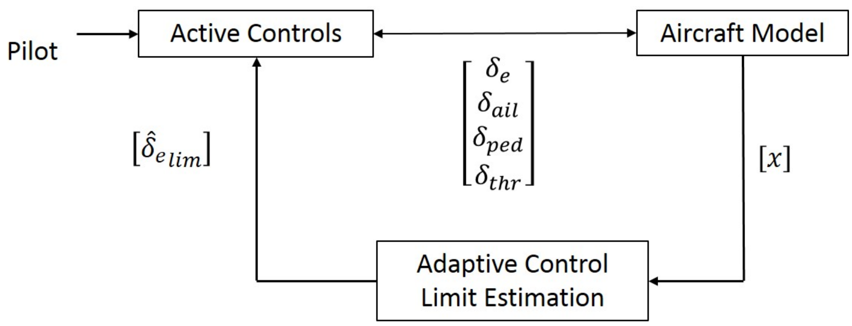


Figure 3.1: Simulation Block Diagram.

considered as the critical parameter and the control margins for elevator are estimated online, where load factor is:

$$n_z = \frac{1}{g}(\dot{w} + vp - uq) + \cos\theta\cos\phi \tag{31}$$

Here, load factor response is dominated by pitch rate (q). Therefore, a model of the pitch rate is generated and load factor is calculated later using Eq.(31).

$$\hat{q} = A_1^{-1}([\hat{\partial}_q \hat{\partial}_\alpha] - B\delta_e) + \Delta(\hat{\partial}_q \hat{\partial}_\alpha, U, \theta, \delta_e, b_1) \tag{32}$$

Here, the first term is the approximate inverse model and the second term is neural network augmentation. $\hat{\partial}$ indicates state derivative estimations.

The steady-state value, $\hat{q}_{SS}$, can be calculated by implementing Eq. (32) and inserting zero to derivative terms:

$$\hat{q}_{SS} = -A_1^{-1}B\delta_e + \Delta(0, 0, U, \theta, \delta_e, b_1) + e \tag{33}$$

where, the approximation error is $e = q - \hat{q}$. The basis of SHL, $\Delta = W^T\sigma(V^T\bar{x})$ is:

$$\bar{x} = [\hat{\partial}_q \hat{\partial}_\alpha, U, \theta, \delta_e, b_1] \tag{34}$$

The sensitivity of load factor with respect to elevator input is given by :

$$S_{n_z} = \frac{\partial \hat{n}_{z_{SS}}}{\partial \delta_e} \tag{35}$$

The steady state limit margin is:

$$\hat{n}_{z_{marg_{SS}}} = \hat{n}_{z_{lim}} - \hat{n}_{z_{SS}}. \tag{36}$$

And, the limit margin based on the measured load factor is:

$$\hat{n}_{z_{marg}} = \hat{n}_{z_{lim}} - n_z. \tag{37}$$

Hence, using Eq.(29) , the upper and the lower control limits become:

$$\boldsymbol{\delta}_{e_{lim}} = min\left(\left|\frac{1}{S}\hat{n}_{z_{marg}}\right|, \left|\frac{1}{S}\hat{n}_{z_{marg_{SS}}}\right|\right) + \boldsymbol{\delta}_e \tag{38}$$

3.0.2 Angle of Attack as the Critical Limit Parameter

For this section again consider the simulation block diagram in Figure 3.1. This time, angle of attack is taken as the limit parameter. Angle of attack is estimated using an approximate model inverse and adaptive element as:

$$\hat{\alpha} = A_1^{-1}([\hat{\partial}_q \hat{\partial}_\alpha] - B\delta_e) + \Delta(\hat{\partial}_q \hat{\partial}_\alpha, U, \theta, \delta_e, b_1) \tag{39}$$

As in [13] the steady state value of (α) estimation is used in sensitivity calculations. α sensitivity is also found in similar manner to load factor sensitivity. Finally, limit margin is found as:

$$\hat{\alpha}_{s_{marg}} = \hat{\alpha}_{lim} - \hat{\alpha}_{SS}. \tag{310}$$

Hence, control limit becomes:

$$\hat{\delta}_{e_{lim}} = \frac{1}{S_\alpha}\hat{\alpha}_{marg} + \delta_e. \tag{311}$$

Finally, the control limits calculated in Eq. (38,311) are compared and the most critical one is taken as the current elevator control limit.

3.1 Simulation Results

The aircraft is trimmed at $120kt$ forward speed and a altitude of $2200m$. The limits are taken as $15\deg$ for angle-of-attack and the $3.5g$ for load factor. The first simulation is not piloted and run with pre-specified input scenario. In other simulations inputs are given over the active inceptor, while hard and soft stop tactile cueing methods are used.

3.1.1 Test Scenario 1

In this test case, a pre-specified input scenario is used. As an input, various pitch up pitch down maneuvers are considered. In Figure 3.2 forward speed, altitude, pitch angle and roll angle for the maneuver is displayed. Limit parameters, α and n_z are shown in Figure 3.3. The adaptation is off until SHL-Concurrent Learning starts adaptation at $t = 10s$. In Figure 3.4 the input scenario is shown together with control limit estimates for both load factor and angle of attack. The algorithm automatically selects the smaller control limit for limit avoidance. Angle-of-attack and load factor adaptive weights can be seen in Figure 3.5. After the adaptation is turned on, weights for both parameters converge. Figure 3.6 displays model error, ξ against adaptive element, Δ for both angle-of-attack and load factor. Model error is tracked by adaptive element for angle-of-attack. For load factor, There are slight differences between the model error and adaptive element. However, as Eq. (38) is used for

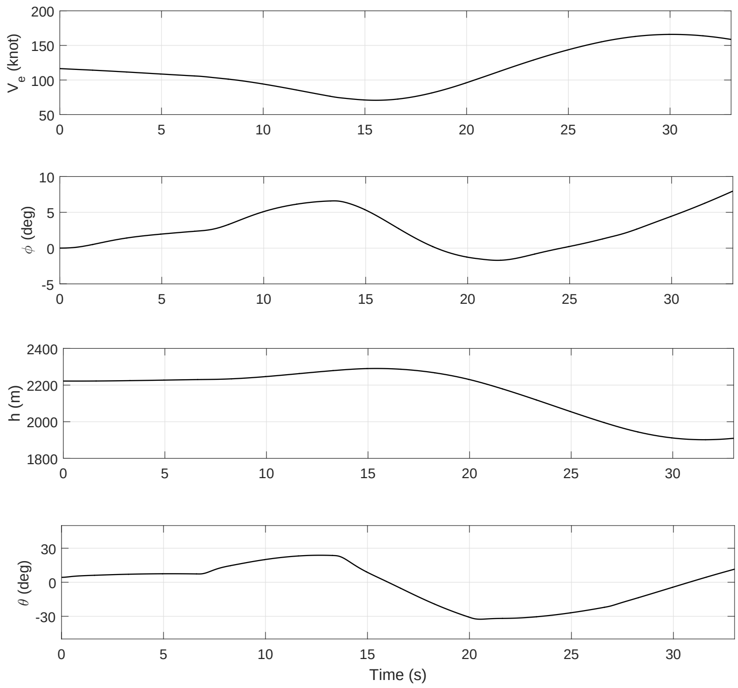


Figure 3.2: Test Scenario 1: Aircraft States

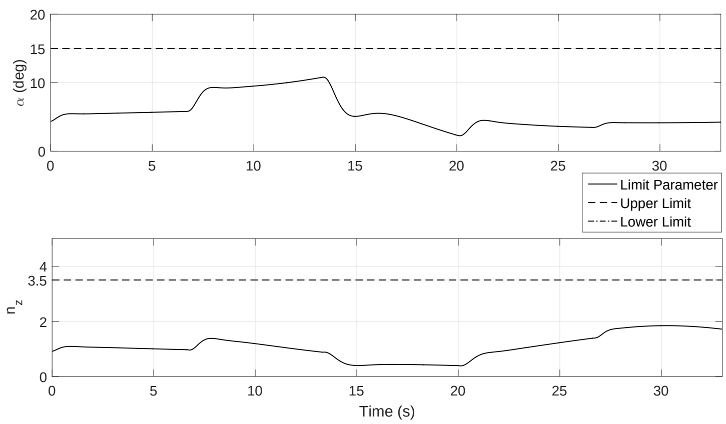


Figure 3.3: Test Scenario 1: Limit Parameters

load factor control limit calculations this difference does not effect limit avoidance performance.

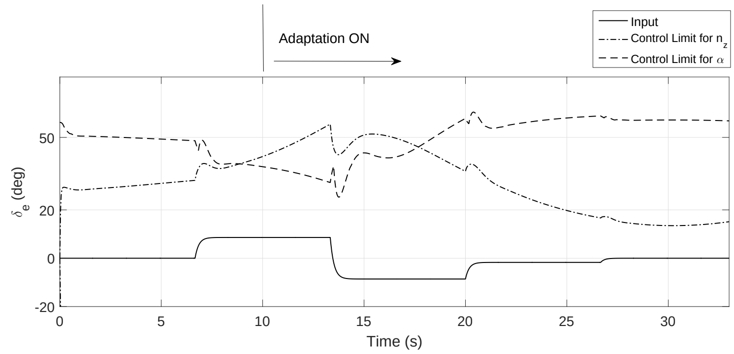


Figure 3.4: Test Scenario 1: Elevator Input and Control Limits

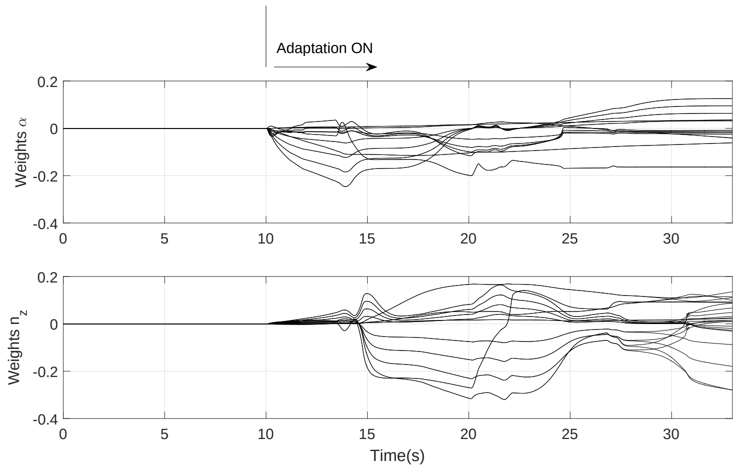


Figure 3.5: Test Scenario 1: Weights

3.1.2 Test Scenario 2: Hard Stop

This scenario uses real time inputs and **hard stop** cueing method is employed via the active inceptor. At envelope limit the stick prohibits further movement in limit exceedance direction; thus, prevents the pilot from running over envelope limits. For this scenario 2 turn maneuvers are made. One with high angle of attack and other with high load factor.

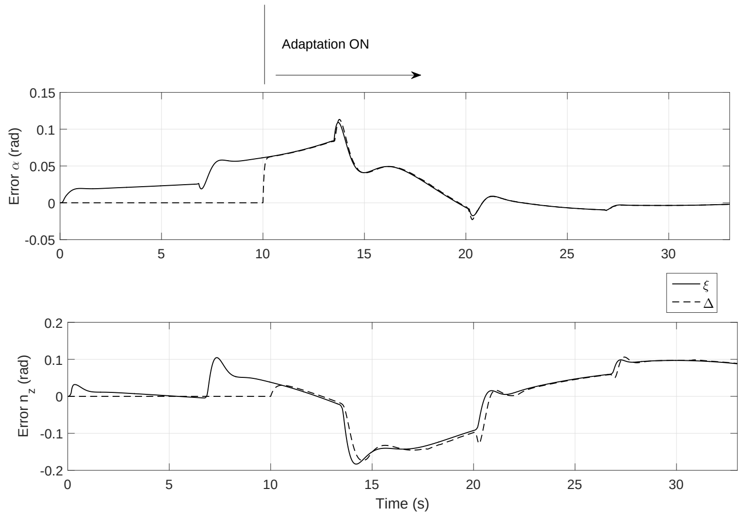


Figure 3.6: Test Scenario 1: Model Error and Adaptive Element

3.1.2.1 High Angle-of-Attack Turn

For the first turn, critical limit parameter is angle-of-attack. In Figure 3.7 forward

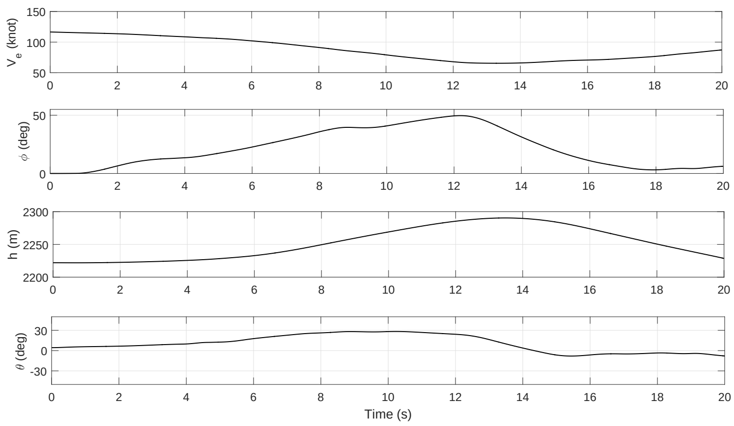


Figure 3.7: Test Scenario 2: Aircraft States for High α Turn

speed, altitude, pitch angle and roll angle for the maneuver is displayed. Limit parameters, α and n_z are shown in Figure 3.8. In Figure 3.9 the input scenario is shown together with control limit estimates for both load factor and angle of attack. Figure 3.10 shows the active inceptor's applied force value over time. In Figure 3.11 adaptive weights of angle-of-attack and load factor are shown. Weights are convergent for both cases. Finally, Figure 3.12 displays model error, ξ against adaptive

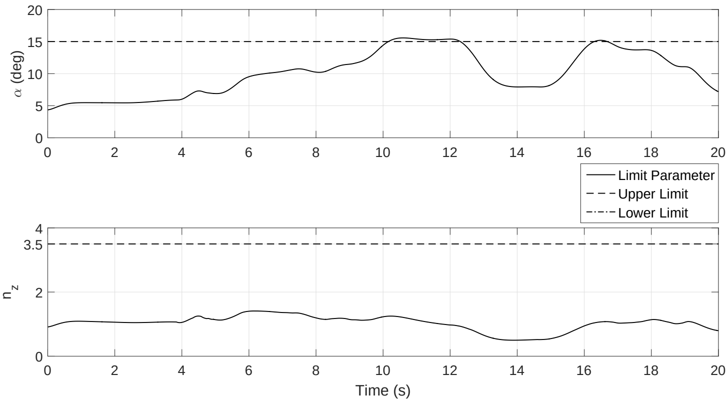


Figure 3.8: Test Scenario 2: Limit Parameters for High α Turn

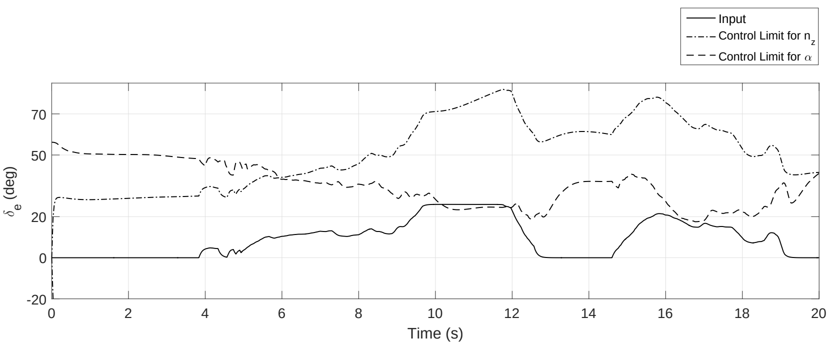


Figure 3.9: Test Scenario 2: Elevator Input and Control Limits for High α Turn

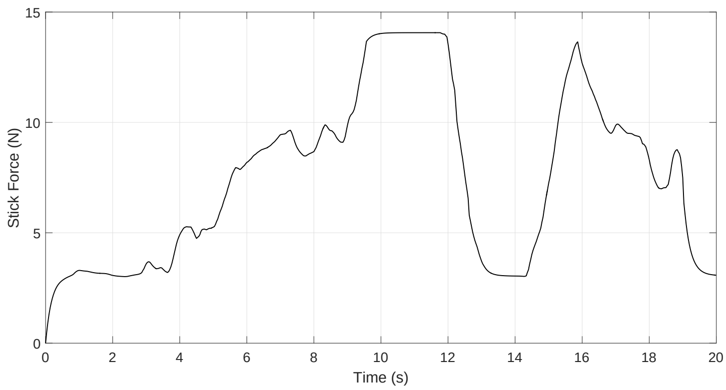


Figure 3.10: Test Scenario 2: Stick Force Feedback for High α Turn

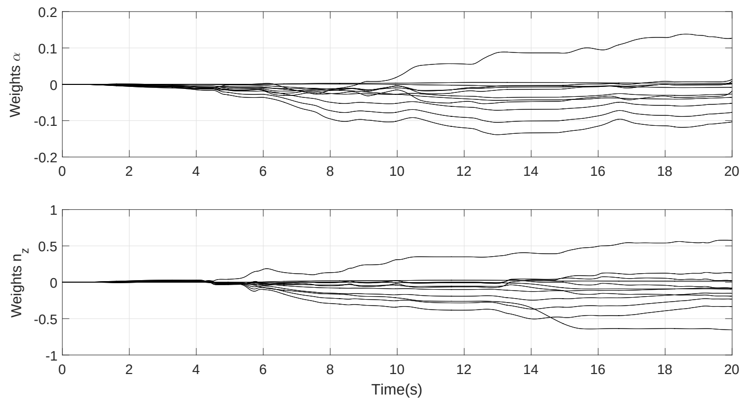


Figure 3.11: Test Scenario 2: Weights for High α Turn

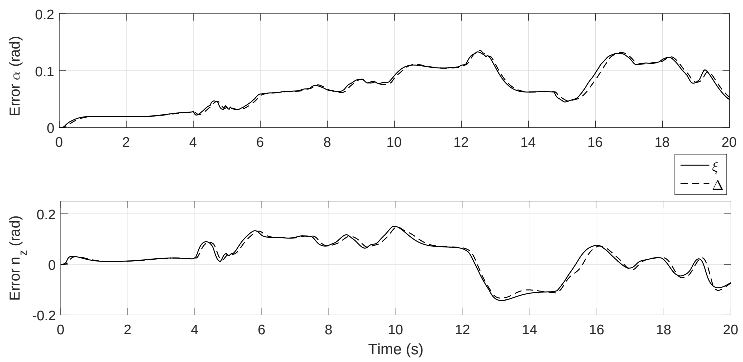


Figure 3.12: Test Scenario 2: Model Error and Adaptive Element for High α Turn

element, Δ for angle-of-attack and load factor.

3.1.2.2 High Load Factor Turn

Load factor is the critical limit parameter for this turn. Limit parameters, α and n_z can be seen in Figure 3.13. Input scenario is shown in Figure 3.14 with laod factor and angle-of-attack control limit estimates. Figure 3.15 shows the force response over time of the active side stick.

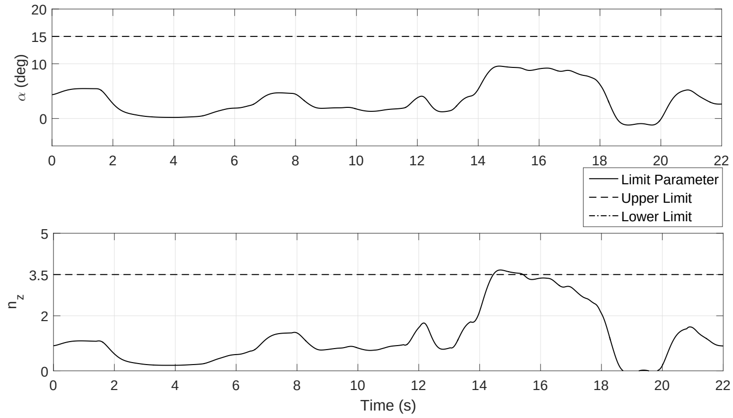


Figure 3.13: Test Scenario 2: Limit Parameters for High n_z Turn

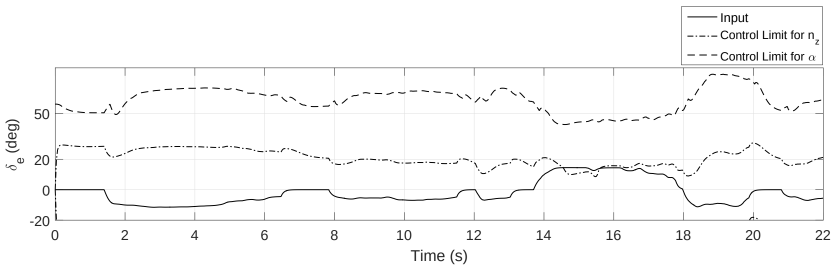


Figure 3.14: Test Scenario 2: Elevator Input and Control Limits for High n_z Turn

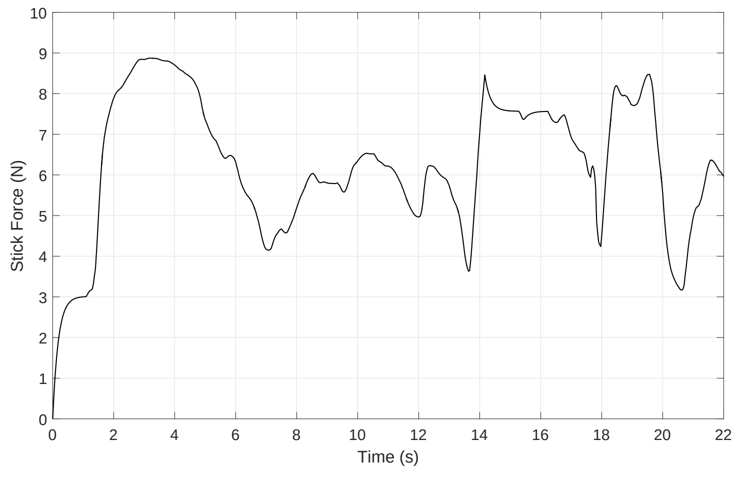


Figure 3.15: Test Scenario 2: Stick Force Feedback for High n_z Turn

3.1.3 Test Scenario 3: Soft Stop

This scenario uses real time inputs and **soft stop** cueing method is employed via the active inceptor. At envelope limit the stick steeply increases required force to prevent the pilot from exceeding limit boundaries. However, if the pilot chooses to go beyond limits, the required force to move the stick further can be over come. Again, two turn maneuvers are made. One for high angle-of-attack and other for high load factor. For both cases the input is stopped by the active inceptor and intentional limit exceedance is made by applying a greater force to the stick.

3.1.3.1 High Angle of Attack Turn

In this turn angle-of-attack is on limit boundaries. In Figure 3.16 forward speed,

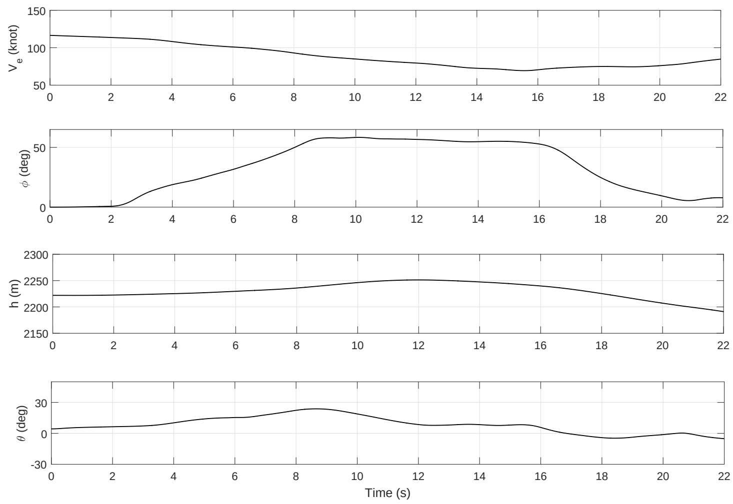


Figure 3.16: Test Scenario 3: Aircraft States for High α Turn

altitude, pitch angle and roll angle for the high angle-of-attack maneuver is displayed. Limit parameters α and n_z can be seen in Figure 3.17. At $t = 8s$ as the aircraft reaches the angle of attack limit and the active inceptor initiates cueing and further movement of the stick is stopped. Then at $t = 12s$ by intentionally applying more force to the inceptor, the angle-of-attack limit is passed. In Figure 3.18 the given inputs are shown together with control limit estimates for both limit parameters. Figure 3.19 shows the force feedback given by the active stick. At $t = 8s$, envelope limit, it can

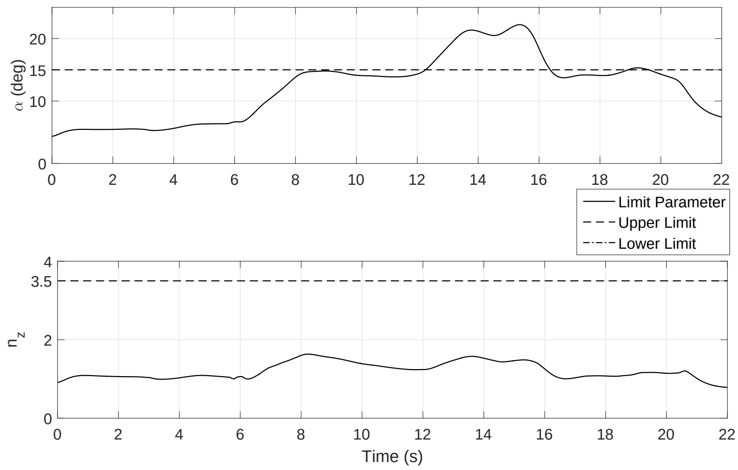


Figure 3.17: Test Scenario 3: Limit Parameters for High α Turn

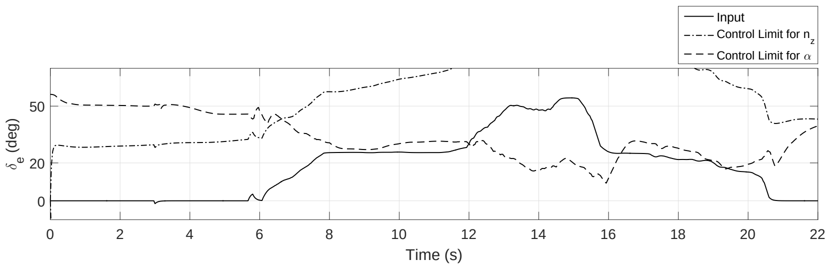


Figure 3.18: Test Scenario 3: Elevator Input and Control Limits for High α Turn

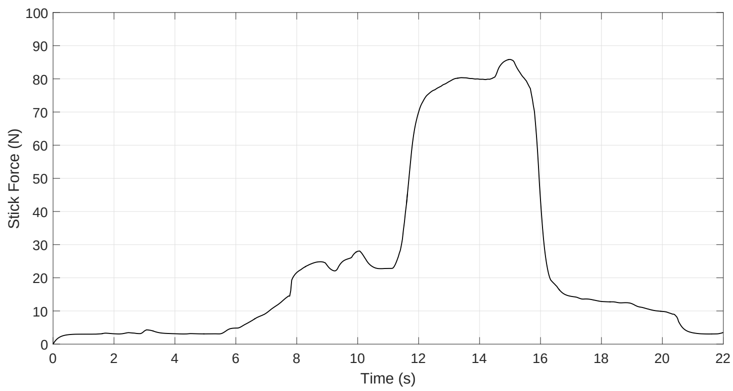


Figure 3.19: Test Scenario 3: Stick Force Feedback for High α Turn

seen that how the stick gives a large force feedback and limit exceedance is avoided. After, to pass the soft stop poiont more force is applied intentionally thus, angle-of-attack limit is passed. In Figure 3.20 adaptive weights for angle-of-attack and load

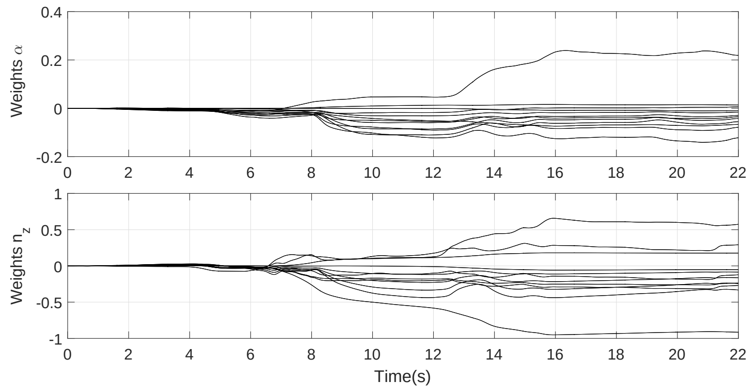


Figure 3.20: Test Scenario 3: Weights for High α Turn

factor and their convergence can be seen. Finally, Figure 3.21 displays model error,

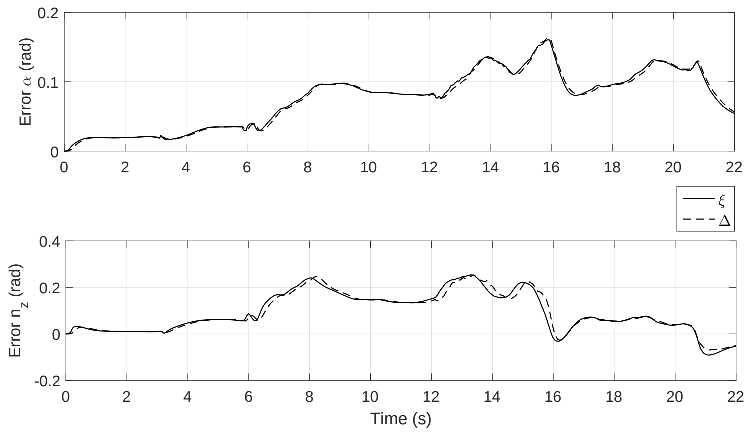


Figure 3.21: Test Scenario 3: Model Error and Adaptive Element for High α Turn

ξ against adaptive element, Δ for angle-of-attack and load factor.

3.1.3.2 High Load Factor Turn

The load factor is the critical parameter for this case. In Figure 3.22 limit parameters

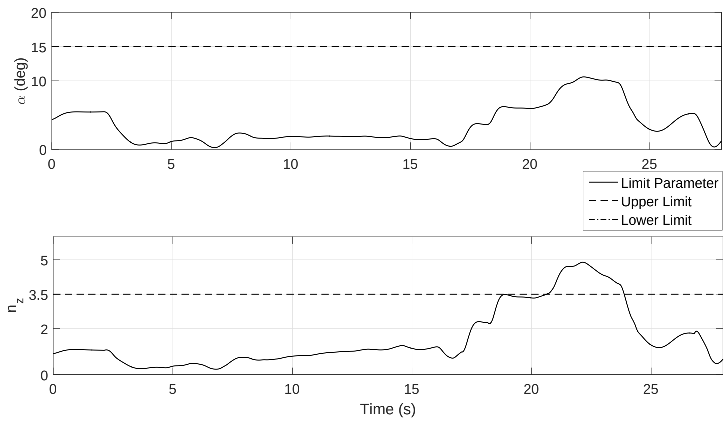


Figure 3.22: Test Scenario 3: Limit Parameters for High n_z Turn

α and n_z are shown. In Figure 3.23 the given inputs and control limit estimates for

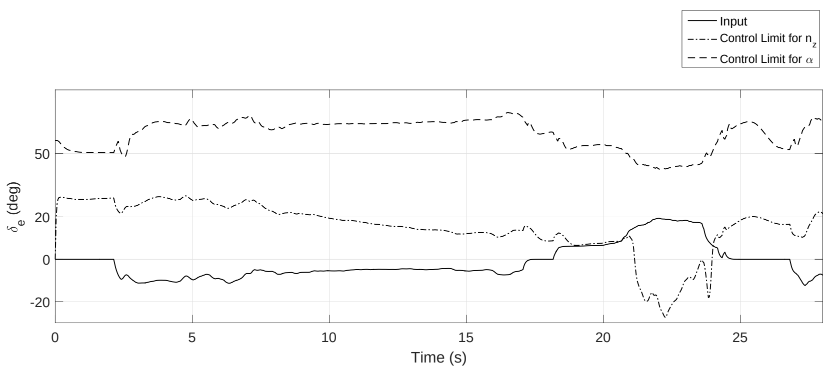


Figure 3.23: Test Scenario 3: Elevator Input and Control Limits for High n_z Turn

both load factor and angle-of-attack are shown. The large variation in n_z control limit is caused from use of Eq.(38). Figure 3.24 shows the force response of the active inceptor. At envelope limit, the stick responds with a large change in force and limit exceedance is avoided. Then, with the intentional application of more force to the stick,load factor envelope limit is exceeded.

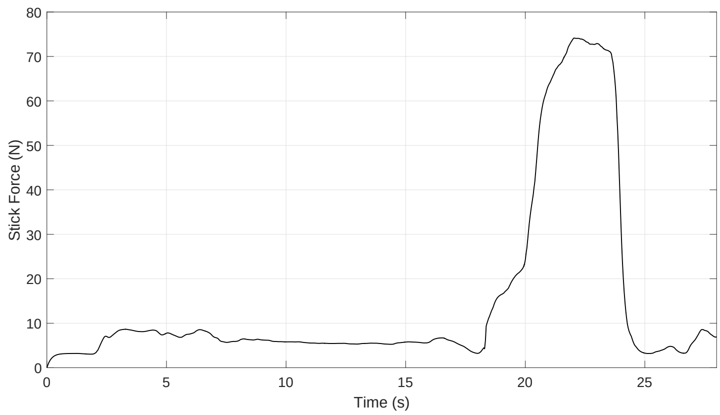


Figure 3.24: Test Scenario 3: Stick Force Feedback for High n_z Turn

3.2 Piloted Simulations

Discussions are made with pilots to find a suitable maneuver to test different cueing methods. As the purpose of these tactile cues are to reduce pilot workload around envelope boundaries, the selected maneuver should incorporate the risks of limit exceedance. In this regard, the initial proposition was test flying the "Box Canyon Turn" could be an appropriate maneuver as generally normal maneuvering procedures are designed such that the aircraft stays in envelope boundaries. The "Box Canyon Turn" is a 180 degree turn where the pilot tries to execute the turn as fast as possible with high bank angle. This turn is somewhat an emergency case scenario where the pilot has to reverse the heading as an obstacle like a mountain is in the flight path. This maneuver was deemed to be sufficient as it is executed with high bank angle. In this maneuver there is risk of exceeding angle-of-attack or load factor, which depends on the speed during the turn. The pilots claimed that the duration of this turn would be short. They have suggested for a longer duration maneuver so that they could have a better feel of the active inceptor and tactile cues during test flights. With this in mind, the "Steep turn" maneuver is selected for the tests. This is again a high bank angle turn made for 360 degrees. In take sake of simulating an emergency, the pilots are tasked to execute the turn as fast as possible.

The aircraft used in the simulations is an high-fidelity model of an single-engined propeller driven aircraft. The angle-of-attack limit is 15 degrees while the load factor limit is 3.8 g.

Table 3.1: Flight hours of test pilots

	Single Engine Fixed-Wing	Two Engine Fixed-Wing	Rotor-Wing	Total Flight Hours
Pilot 1	600	0	1050	1650
Pilot 2	600	1800	250	2650
Pilot 3	100	250	150	500

In table 3.1 flight experience of the pilots participated in the tests can be seen. All three of them are active duty pilots in the Turkish Army. Pilot 1 is much more experienced in helicopters compared to other pilots but still has more flight hours in fixed-winged aircraft compared to pilot 3 who is relatively new in this profession. Pilot 2 has the most flight experience in fixed-wing aircraft compared to other two with most of them on two engine planes.

At the beginning of simulation flight tests, each pilot is given time to freely fly and familiarize with the simulation environment, active stick and its tactile cueing functions. The initial responses were that the default settings for force gradients were high. As the force gradient can be set in real time in this setup, the default force gradient is tuned for a slightly smaller slope and set as the new default for oncoming tests.

For the ratings, each pilot flew the steep turn maneuver one after other for each tactile cueing method with initially starting off with passive mode. After each completion of the maneuver, pilots rated the method on the NASA-TLX questionnaire and their stick inputs are saved. Following parts are divided in subsections for each cueing method. Results for different pilots are given under these subsections. Lower grades on the TLX rating scale indicate better results.

3.2.1 Passive Stick

First, initial tests are made with no cueing methods applied. This is made as a baseline for both pilots and limit avoidance comparisons. Angle-of-attack and load factor plots of the tests are given in Figure 3.25 for all three pilots. As mentioned before, tests are made with the steep turn maneuver. Pilot 1 can be seen passing the limits while pilot 2 and 3 are well below them. The importance of carefree maneuvering systems can be emphasized here as in either case, the aircraft was over the limits or under them with plenty of usable margin left.

The TLX ratings given by pilots, Table 3.2, indicate close results to each other. Pilots were generally happy with the passive mode as this what they are accustomed to. This is reflected in given "mental demand" grades. The "performance" and "effort" grades are mediocre compared to rest which is a result of pilot's need to continuously check the aircraft attitudes and limits simultaneously.

Table 3.2: NASA-TLX grades for passive stick

	Pilot 1	Pilot 2	Pilot 3	Average
Mental Demand	30	25	30	28.33
Physical Demand	30	25	30	28.33
Temporal Demand	50	50	30	43.33
Performance	50	60	50	53.33
Effort	55	40	65	53.33
Frustration	25	25	45	31.67
Total Points	40	37.5	41.67	39.72

3.2.2 Hard Stop

The first cueing method tested is the hard stop cueing method. In this method, the active inceptor blocks further movement of the stick thus prevents limit exceedance. From Figure 3.26 the effectiveness of this cueing method can be seen. With only minimal overshoots, the pilots were able to stay on the limits. Even though the hard stop enabled them for tighter turns without surpassing the limits, the pilot reviews indicate that they were put off by loosing full control over the aircraft and would not prefer hard stops. Also they have commented that with this cueing it was much harder to control the flight path of the aircraft on limit boundaries and had to use the pedals for overcome the dropping of the aircraft's nose. This is due to loss of pitch control introduced by the hard stop. Pilot 1 suggested that this could be improved by introducing fine control by the usage of trim tabs on limit boundaries. This could be achieved by stopping the stick at the limit with a small margin of control axis movement available for controlling the trim tabs.

Compared to the passive mode, bad notes are given for the hard stop. Table 3.3 shows substantial increase on given points especially for "physical demand", "performance" and "frustration". Even though the pilots knew the hard stop would not let them pull the stick any further on the limits, they instinctively tried to pull the stick to maneuver the plane as they desired. This become tiresome to the pilots as they started to fight with the stick. Which in turn effected the flight performance of the maneuver and caused frustration. However, it should be noted that as the pilots get familiar to the cueing method, they learned to not apply excessive force to the stick but just simply hold it in position. This can result in better ratings overtime yet pilots would still be unpleased with limitations caused by the hard stops.

Table 3.3: NASA-TLX results for hard stop cueing

	Pilot 1	Pilot 2	Pilot 3	Average
Mental Demand	35	20	40	31.67
Physical Demand	50	35	50	45
Temporal Demand	40	35	25	33.33
Performance	70	50	65	61.67
Effort	40	70	75	61.67
Frustration	65	60	65	63.33
Total Points	50	45	53.33	49.44

3.2.3 Soft Stop

The soft stop cues have a sudden increase in required forces to move the stick. This effectively stops the pilot's stick movement on limit boundaries. The pilot is able to pass this point by exerting more force to the inceptor. This prevents unintentional limit exceedance while allowing full control over the aircraft by letting intentional exceedance of control limits. This can easily seen in Figure 3.27 where Pilot 2 used the cues to stay in the limits while Pilot 1 and 3 momentarily paused at the limits before passing them. An interesting point to note would be that Pilot 1 was able to easily pass the stop at around 15 seconds and 20 seconds of Figure 3.27a. This marks the importance of finely tuning the general force profile as to small a force difference requested by the stop would render it ineffective while too much of a force difference would challenge the pilots. This is a difficult task as each pilot's physical strength and preferences are different.

Looking over the TLX results in table 3.4, it can easily seen that soft stop got better grades in all aspects except mental demand compared to the hard stop method. As the hard stop prevents any further movement of the stick towards limit exceeding direction while on limit boundaries, the pilots have one less task to think about opposed to the soft stop. But pilots mentioned better attitude control due to the soft stop's non-restrictive nature over aircraft control, which resulted in much better overall grades.

3.2.4 Shaker

Flights made with the shaker method of cueing can be seen in Figure 3.28. The shaker does not alter the predefined force gradient of the inceptor but only starts to shake the stick onset of limit boundaries. The shake frequency and amplitude can be changed but the pilots were happy with default settings. Pilot 2 and 3 were able to fly on the edge of limit boundaries and make a sharper turn compared to their maneuvers in passive stick mode. Pilot 1 made a much more aggressive turn compared to the other two. He has used the information given by the shaker to stay over the limit boundaries. This can clearly seen in Figure 3.28a, at around 20-21 seconds the aircraft drops

Table 3.4: NASA-TLX results for soft stop coeing

	Pilot 1	Pilot 2	Pilot 3	Average
Mental Demand	35	30	35	33.33
Physical Demand	35	25	40	33.33
Temporal Demand	40	25	25	30
Performance	30	35	40	35
Effort	50	40	55	48.33
Frustration	30	40	40	36.67
Total Points	36.67	32.5	39.17	36.11

below the angle-of-attack limit thus the shaker stops and the pilot immediately pulls the stick more for a tighter turn. This is oppose to how pilot 2 and 3 used the shaker. In their case, they have backed off from the stick, when the shaker was activated, to stay in limit boundaries. This highlights different pilots "styles" and how this method attains full control of the aircraft. Which, is praised by the test pilots. Also, all three pilots noted that the feel of feedback given by the shaker is close to what they are used to on aircraft and they got accustomed to it easily as it sharply alerts the user like visual or aural cues but does not surprise the user with a sudden change on force gradients.

Pilot grades given to the shaker are similar to soft stop method, Table 3.5. This makes the shake one of the more preferred methods of cueing. As the shaker method does not alter the force gradient of the inceptor, forces felt by the pilot are the same with the passive stick mode which the pilots are familiar. This familiarity ensured less mental, physical and temporal demand to the pilots thus resulted better grades in these dimensions. Also this similarity with the passive mode caused poor grades on the other dimensions compared to the soft stop. Performance, effort and frustration suffered because there is a lack of aid given by a physical stop to follow the task while staying on limit boundaries.

Table 3.5: NASA-TLX results for shaker cueing

	Pilot 1	Pilot 2	Pilot 3	Average
Mental Demand	35	30	30	31.67
Physical Demand	30	15	30	25
Temporal Demand	40	20	25	28.33
Performance	55	45	45	48.33
Effort	35	60	40	45
Frustration	30	45	50	41.67
Total Points	37.5	35.83	36.67	36.67

3.2.5 Variable Gradient Hard Stop

This cueing method does not have one set of defined force gradient but it steepens as the available control margin decreases. And like the standard hard stop, it prohibits limit exceedance. As seen by the Figures in 3.29, non of the pilots were able to pass the limits. In fact in all three cases the aircraft stayed in the safe flight envelope. One interesting point to note is in the case of Pilot 2, the aircraft still had a margin in its angle-of-attack limits. Of course aircraft are need not to be flown on their limits all the time but in these tests pilot were trying to fly on or above the limits as defined in the test maneuver and the reason of the available limit margin in Figure 3.29b is that the force gradient of the inceptor became to steep and the pilot had problems moving the stick any further. This is also reflected in the TLX results. A similar case happened to Pilot 3 between 20 and 30 second marks in Figure 3.29c. Even though this method is successful in holding the limits, it is disfavored by the pilots because continuously changing force gradient and excessive force requirements on limit boundaries discomfort the pilots.

Pilots did not like the continuously changing force gradient of the variable gradient mode because it did not allow them to have a clear idea of how would the force change on the upcoming steps. Also, the steep increase in required force towards limit boundaries is found to be negative. These issues coupled with the negative effects of the standard hard stop, grades given by pilots suffered significantly.

Table 3.6: NASA-TLX results for variable gradient hard stop cueing

	Pilot 1	Pilot 2	Pilot 3	Average
Mental Demand	40	40	40	40
Physical Demand	65	50	50	55
Temporal Demand	55	25	35	38.33
Performance	65	35	70	56.67
Effort	65	65	55	61.67
Frustration	65	55	70	63.33
Total Points	59.17	45	53.33	52.5

3.2.6 Variable Gradient Soft Stop

Similar to the previous method, the force gradient steepens as control margin decreases. The difference lies in the final force value the stick reaches at the limit and how it changes after. As the force value of the inceptor reaches at the limit is lower compared to variable gradient hard stop and the fact that force increases with a much smaller slope after the limits, ensure the pilots full control over the aircraft with much less physical demand compared to the hard stop version of this cueing method. This was also noted by the pilots and reflected in their NASA-TLX questionnaires. The effectiveness of this method is demonstrated in Figure 3.30 where it can easily observed that pilots were initially stopped at the limit boundaries and they were able to pass these limits on demand.

Similarly to the previous case, variable gradient cause bad comments and grades. The soft stop component of the cue improved the results compared to variable gradient with hard stop but, the overall performance still suffered compared to other tactile cue methods tested in this work.

Table 3.7: NASA-TLX results for variable gradient soft stop cueing

	Pilot 1	Pilot 2	Pilot 3	Average
Mental Demand	50	20	25	31.67
Physical Demand	55	55	60	56.67
Temporal Demand	50	30	30	36.67
Performance	40	40	75	51.67
Effort	55	60	60	58.33
Frustration	40	45	50	45
Total Points	48.33	41.67	50	46.67

3.2.7 Hard Stop with Shaker

As in other hard stop cues, this method too does not allow any limit exceedance. The difference lies in the combination of two separate cues, hard stop and shaker. The advantage of this lies in the initial warning given by the shaker of oncoming limit boundaries. By this way, the pilot knows that the aircraft is close to limits and can expect hard stop initiation. This takes away the surprise given by sudden activation of the stop in plain hard stop cueing. Indeed this property is liked by pilots which can be seen from the NASA-TLX grades given by the pilots. In Figure 3.31 it can be observed that this method effectively prevents limit exceedance. Also, pilots were able to hold the aircraft under but close to the limits by just using the shaker function. This can seen easily between 18-20 seconds in Figure 3.31a for Pilot 1 and around 15 seconds for Pilot 3 in Figure 3.31c.

Interestingly, the addition of the shaker to the hard stop significantly improved its grades. Also, pilot comments reversed overall all and became positive. This improvement is attributed to the shaker as it warns the pilot before hand the upcoming limit boundaries. With this warning, pilots know the hard limit is about to trigger so they can arrange themselves. This resulted in less force used by the pilot which affected the TLX elements in a positive way.

Table 3.8: NASA-TLX results for hard stop with shaker cueing

	Pilot 1	Pilot 2	Pilot 3	Average
Mental Demand	50	35	20	35
Physical Demand	35	10	30	25
Temporal Demand	50	20	15	28.33
Performance	35	40	40	38.33
Effort	30	60	60	50
Frustration	40	25	35	33.33
Total Points	40	31.67	33.33	35

3.2.8 Soft Stop with Shaker

Soft stop with shaker is the last cueing method tested in this study. Similarly to the previous method, cueing is made by combination of two distinct cues. At a predefined limit margin the stop stop activates to alert the pilot of closing limit boundaries and if the pilots chooses to pass this point, the shaker initiates if the plane reaches the limits. According to pilot commentary, this method is found to be the most useful and favorable compared to others tested. In Figure 3.32 pilots can be observed to hold the limits smoothly initially and pass over the limits on purpose. The difference between this cue and with only using the soft stop lies in aircraft control on limit boundaries. Even though using the soft stop is better at controlling the aircraft states on limit boundaries compared to hard stops, soft stop with shaker improves this advantage. During the tests it is observed that as the pilots are initially warned with the soft stop before actual limits, they intuitively arrange their input rates expecting the shaker to initiate next. This, coupled with the constant force gradient slope ensuing the soft stop point, enabled smoother control of the aircraft around limit boundaries.

Correlatively with the previous case, the addition of shaker to the soft stop improved results over the single soft stop cueing case. Pilots do not suddenly find themselves on the limit but approach it in a two step manner while still attaining full control of the aircraft. This, resulted in improvements an all elements of the TLX compared to the single soft stop. The overall results show that it is the most favored cueing method tested in this study. Still, the physical demand element is higher compared to passive, shaker and hard stop with shaker modes. This is because the required force to move the inceptor beyond limits is higher compared to them. Tuning this area for a lesser gradient could further improve this cueing method.

Table 3.9: NASA-TLX results for soft stop with shaker cueing

	Pilot 1	Pilot 2	Pilot 3	Average
Mental Demand	35	25	25	28.33
Physical Demand	35	25	35	31.67
Temporal Demand	30	10	20	20
Performance	10	35	35	26.67
Effort	40	45	25	36.67
Frustration	20	30	35	28.33
Total Points	28.33	28.33	29.16	28.61

3.2.9 Comments and Suggestions of Pilots

Below are the compilation of comments given by the pilots after the tests were made.

- Soft stop with shaker and hard stop with shaker are much better options compared to others
- Hard stop doesn't feel useful and feels challenging in holding the limit while also holding the aircraft attitude. It can be improved by allowing maneuvering with trim tabs while the hard stop is activated. This way, the pilot can fine tune the maneuver on the limit
- Pilot controls should not be too soft. That being said, variable gradient stops are nice but should not be too hard at slow speeds and high load factors. Should be set for different flight regimes.
- In soft stop with shaker, even though the force gradient does not change after stop soft is initiated, the pilot feels a relief in force after the shaker is activated.
- These systems can have more positive responses with new generations of pilots because of differences in habits
- Force gradients should be tuned with high number of pilots with the best candidates of cueing methods.
- Hard stop should only be used for flight critic parameters. ie, never pass limits like the g-limit of an aircraft. Angle-of-attack limits can be overshot so hard stop is not the best option for such a limit.
- Soft stops are more confidence giving as it still attains full control over the aircraft. The flexibility of limits should be usable if necessary.
- The feeling of the shaker cueing method is much better compared to hard and soft stops. It gives the feeling of "something is wrong" much better.
- The force gradients feel too heavy after passing soft stop points.
- Soft stop with shaker seems the best compared to other methods as it gives the pilot full control while giving good cues of something is going wrong.

3.2.10 Cueing Method Comparisons

The grades given to the methods from previous sections are gathered in Table 3.10. Hard stop variations are very good at holding limits compared to other methods but they suffer at controlling the aircraft attitude on the limit boundaries. Pilots often found themselves applying excessive force and additional control inputs like pedals for example holding the nose which resulted in bad grades compared to others.

Variable gradient versions of the cues also suffered bad grades which is mainly caused by the continuously changing force profile and steeply increasing force demand towards limits. The hard stop version of the variable gradient gathered unfavorable properties of both cases which resulted the worst grades in this study. Changing the hard stop with soft stop in the variable gradient cues improved the results but negligibly.

The shaker cue is liked by the pilots which they have commented that it gives the "something is wrong" feeling very well on limit boundaries when the shaker is activated. With its identical force gradient to passive stick and convenient cueing shaker method got good results.

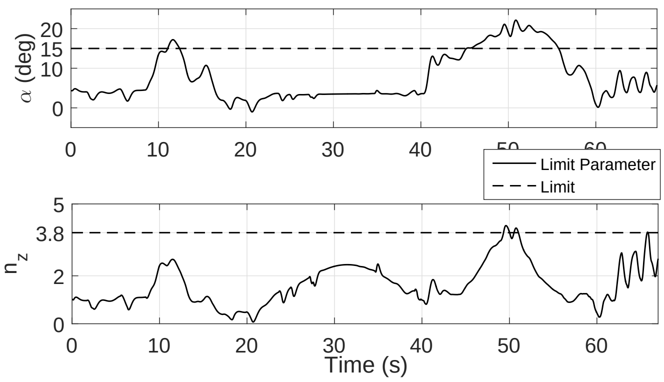
As soft stop retains full control over the aircraft pilot easily maneuvered the aircraft on limit boundaries easily. Only concern is beyond limit boundaries demanded force is high which effects effort and physical demand elements of the TLX grading. Overall all soft stop resulted in third best cueing method tested in this work.

Addition of shaker to the hard stop cue improved the results considerably. From being one of the worst methods tested when combined with the shaker, hard stop resulted with the second highest grades in this work. This is attributed to the early warning given by the shaker and enough time it gives to the pilots so they can arrange themselves accordingly.

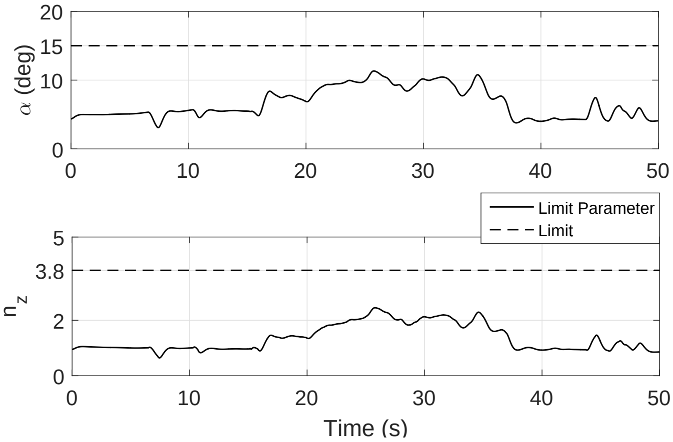
Similarly to the previous case, shaker improved the soft stop results even further. With the two step warning of combined cues and full aircraft control preserved by the soft stop, soft stop with shaker resulted being the most favored cueing method tested in this study.

Table 3.10: NASA-TLX results compared between tested tactile cues

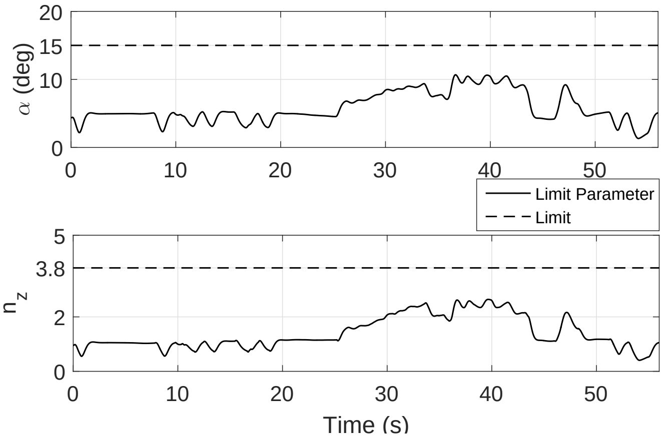
	Mental Demand	Physical Demand	Temporal Demand	Performance	Effort	Frustration	Total Points
Passive	28.33	28.33	43.33	53.33	53.33	31.67	39.72
Hard Stop	31.67	45	33.33	61.67	61.67	63.33	49.44
Soft Stop	33.33	33.33	30	35	48.33	36.67	36.11
Shaker	31.67	25	28.33	48.33	45	41.67	36.67
Variable Gradient Hard Stop	40	55	38.33	56.67	61.67	63.33	52.5
Variable Gradient Soft Stop	31.67	56.67	36.67	51.67	58.33	45	46.67
Hard Stop with Shaker	35	25	28.33	38.33	50	33.33	35
Soft Stop with Shaker	28.33	31.67	20	26.67	36.67	28.33	28.61



(a) Pilot 1

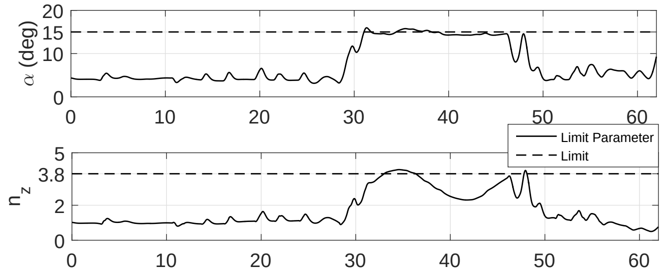


(b) Pilot 2

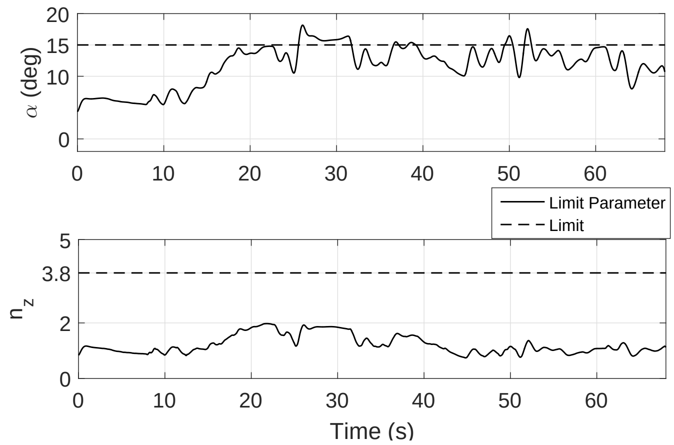


(c) Pilot 3

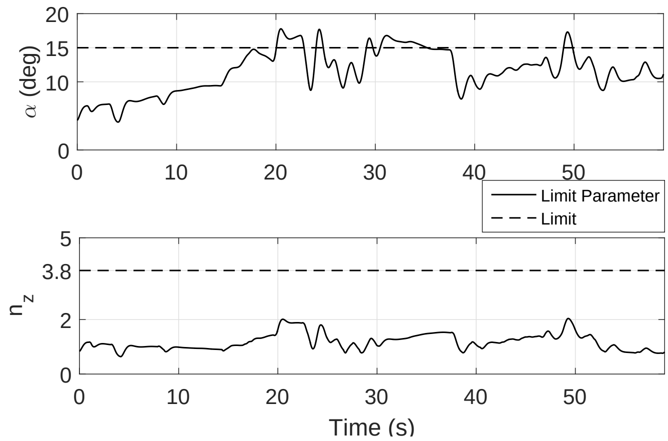
Figure 3.25: Flights made with passive stick mode



(a) Pilot 1

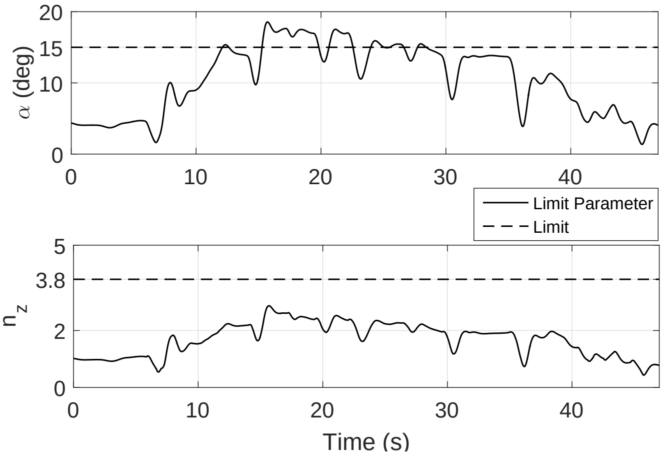


(b) Pilot 2

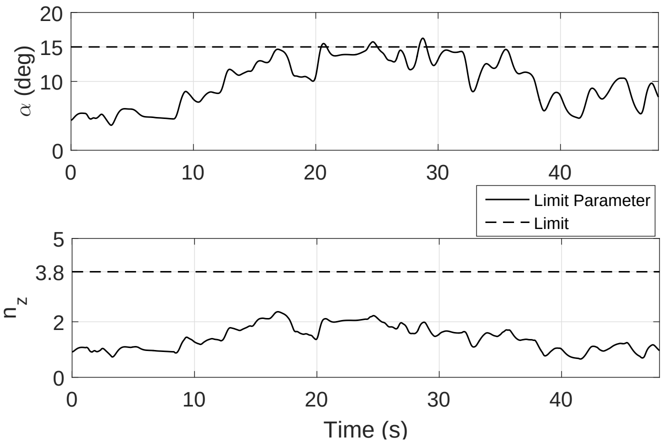


(c) Pilot 3

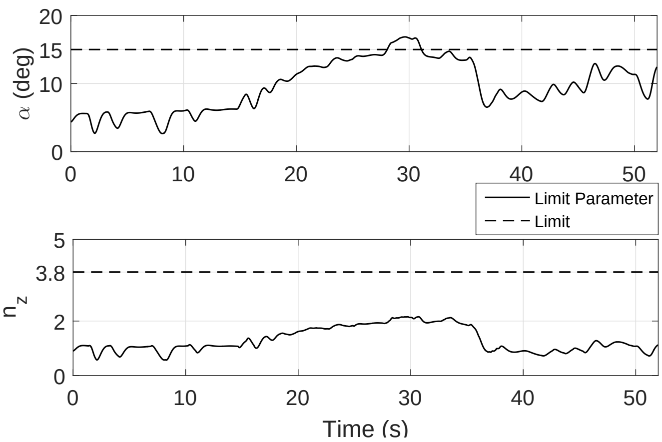
Figure 3.26: Flights made with hard stop cueing



(a) Pilot 1

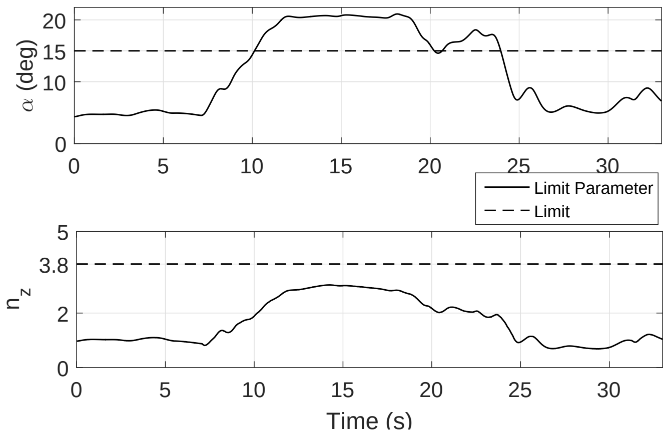


(b) Pilot 2

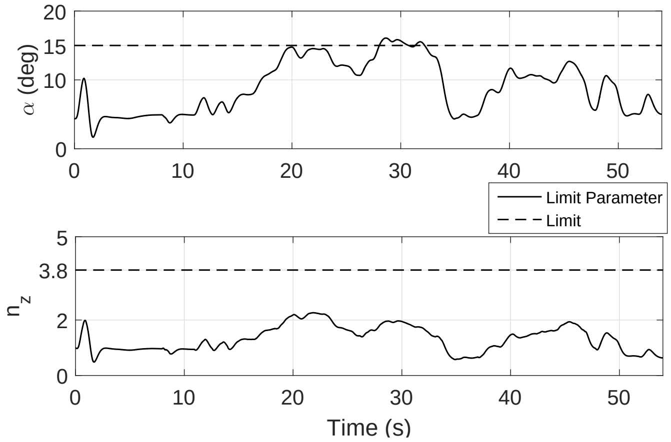


(c) Pilot 3

Figure 3.27: Flights made with soft stop cueing



(a) Pilot 1



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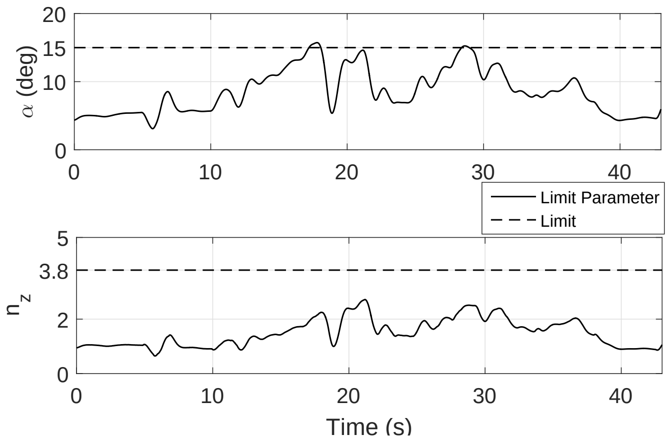
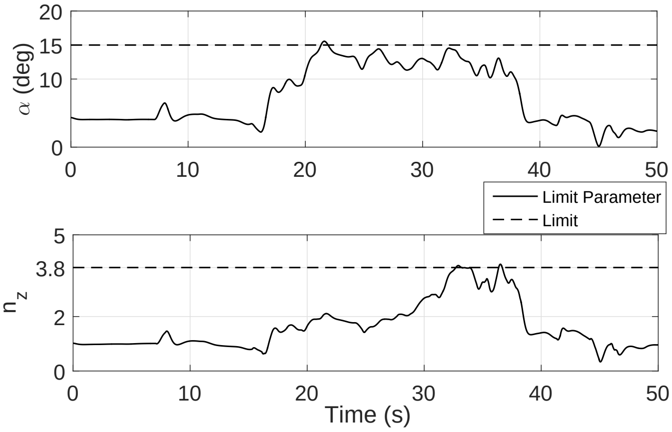
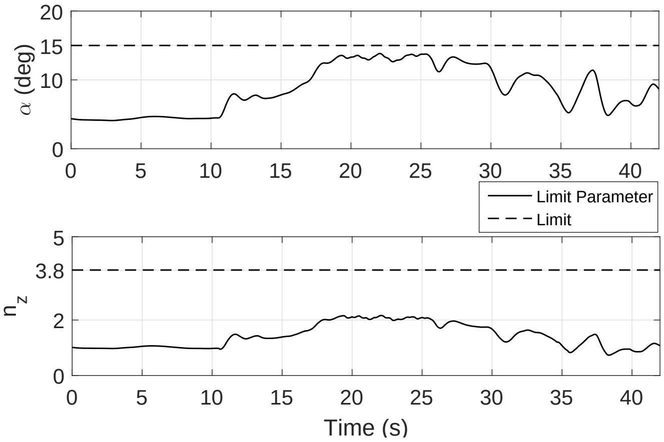


(c) Pilot 3

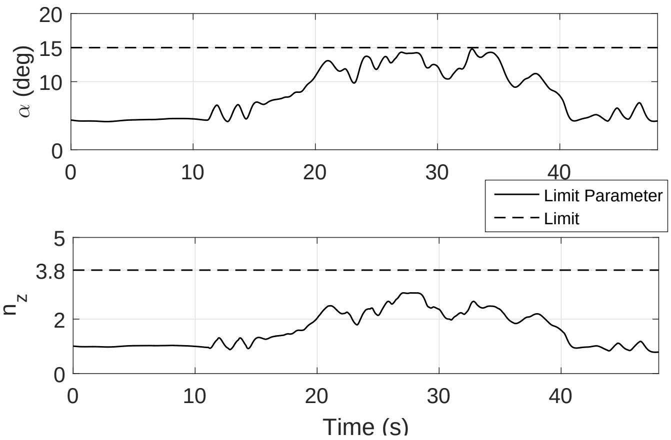
Figure 3.28: Flights made with shaker cueing



(a) Pilot 1

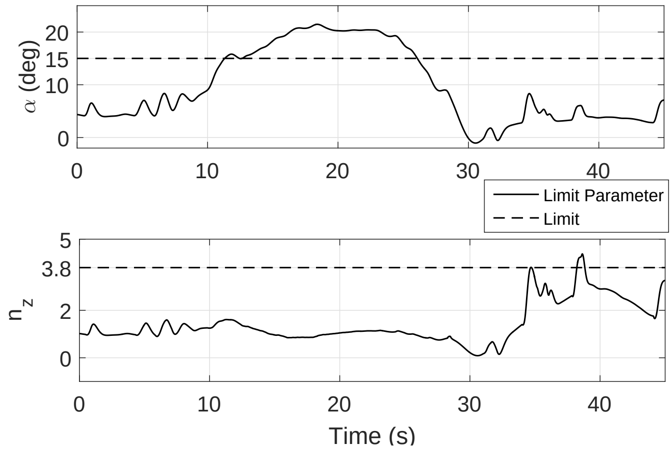


(b) Pilot 2

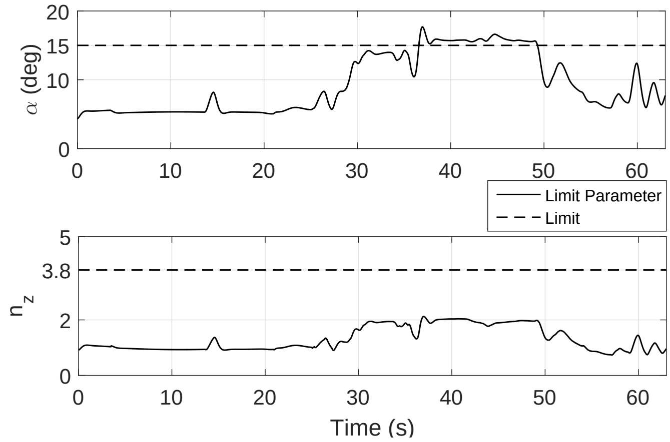


(c) Pilot 3

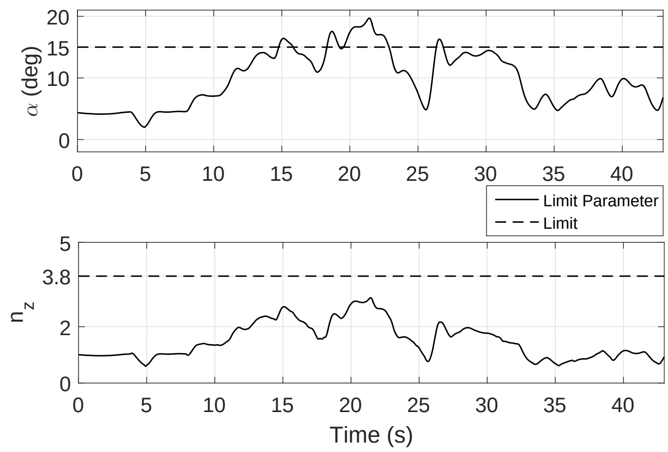
Figure 3.29: Flights made with variable gradient hard stop cueing



(a) Pilot 1

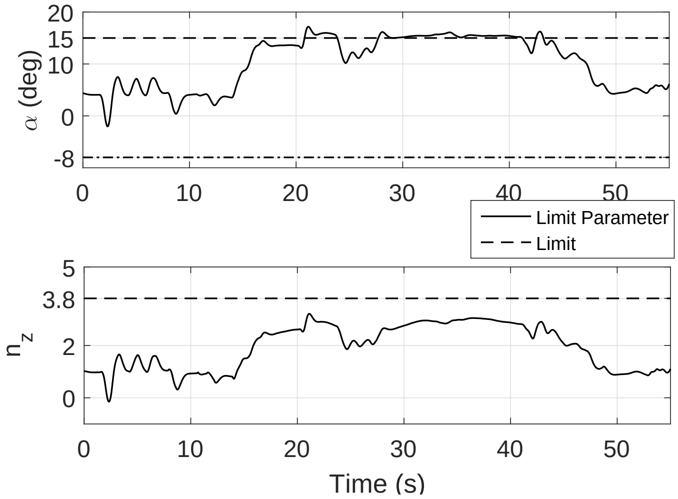


(b) Pilot 2

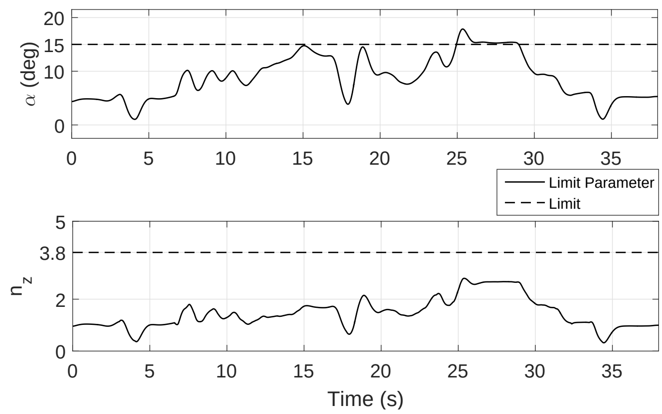


(c) Pilot 3

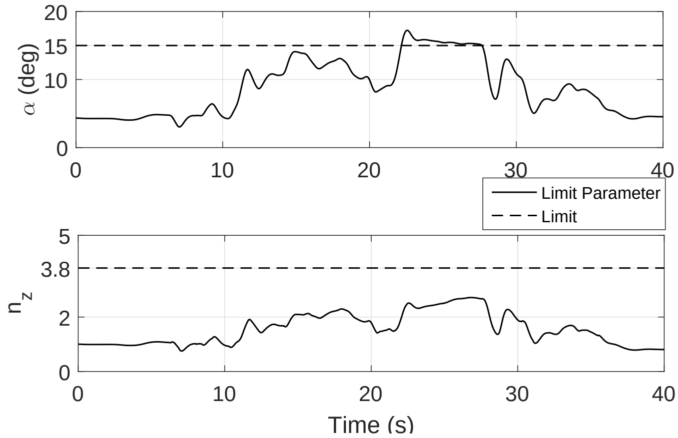
Figure 3.30: Flights made with variable gradient soft stop cueing



(a) Pilot 1

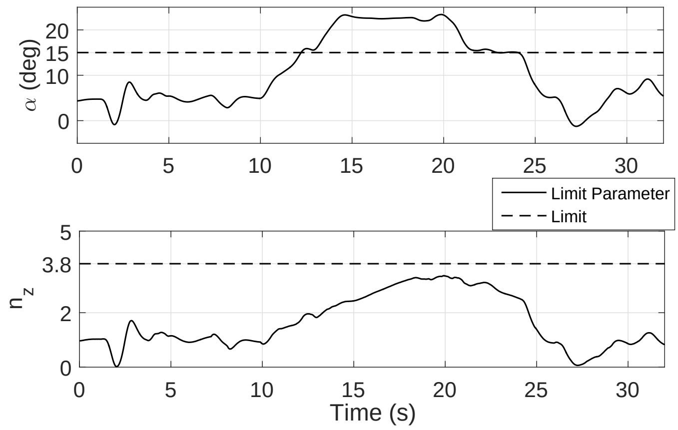


(b) Pilot 2

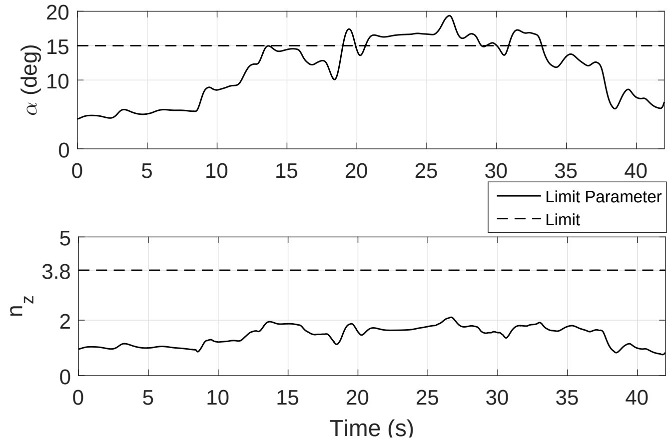


(c) Pilot 3

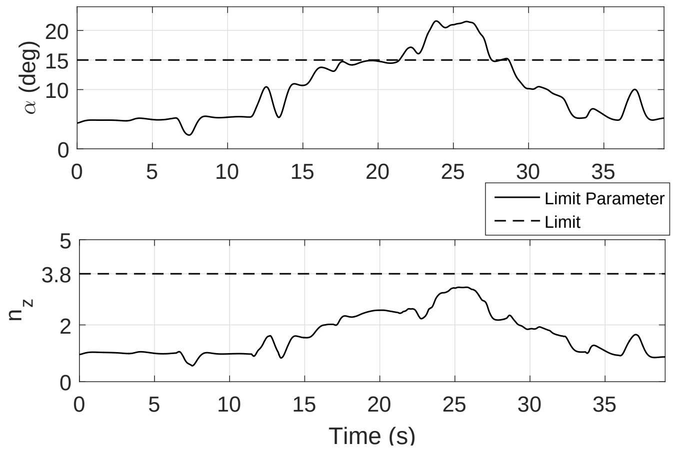
Figure 3.31: Flights made with hard stop with shaker cueing



(a) Pilot 1



(b) Pilot 2



(c) Pilot 3

Figure 3.32: Flights made with soft stop with shaker cueing

CHAPTER 4

CONCLUSIONS

Aircraft have envelope limits which should not been exceeded. Pilots continuously monitor these limit parameters while doing other tasks related to their flight. This effectively increases their workload. Carefree Maneuvering Systems aim to help in this matter by taking away the task of monitoring limits from the pilot. This is done by estimating upcoming limit boundaries and cueing the pilot in a timely matter. The effectiveness of these systems on fly-by-wire aircraft can be increased by using active inceptors. With the ability to continuously change the force characteristics of the active inceptor, tactile cues can be given to the pilot.

In this study, a simulation environment around a Stirling Dynamics Next Generation Inceptor is established. The simulator can be both used for fixed and rotary-wing aircraft. For both cases a high fidelity aircraft model is used and the Direct Adaptive Limit Margin Estimation method is integrated to predict limits of these aircraft. With the use of these predictions, the pilots are informed of upcoming limit boundaries with various tactile cues via the active inceptor.

Piloted tests are made on the simulation environment to see the effectiveness of tactile cueing and comparing different methods with each other. Test results show that as tactile methods are a viable and effective option to cue the pilot, it cannot be concluded that every option of tactile cueing is better than not using any tactile cues. This is seen in outcomes of the NASA-TLX workload rating and pilot comments. In a few methods, namely, hard stops and variable gradient stops it is seen that even though envelope violations were avoided the pilots could not maneuver easily and had to use excessive force. This caused fatigue while also causing frustration as the pilots were pushed to use other controls to hold the attitude of the plane as required by the task.

As opposed to these, the two step cueing methods were favored by the pilots. This is also reflected in the workload rating scale were hard stop with shaker and soft stop with shaker shows substantial improvements compared to other cueing methods. Between the two, pilot reviews show that soft stop with shaker is a better option as it allows the pilot to have higher authority over the aircraft and can fly on the envelope boundaries with ease.

Even though methods that include hard stops were not favored, it is shown that these hold the aircraft on the limits very well. This indicates that methods that include hard stops can be very useful where the exceedance of limit parameter will be catastrophic. As opposed to such limits, methods including soft stops and shakers proved to be useful where small overshoots of the limit parameter are acceptable or necessary in emergency situations.

4.1 Future Work

Considering the results obtained in this work, following items care considered to advance this work.

- As the force stop with shaker cue method is deemed the best compared to other methods in this work, it could be further improved. The force profile after the soft stop could be tuned with a lesser force gradient. This would result in better physical demand and effort grades as the required force to move the stick above limit boundaries would be less. Overall, with a re-tuned profile this method could result in even be better grades.

- To further improve the statistical data gathered, same tests could be conducted with more pilots. Also doing these tests with relatively new pilots with less experience could be another thing to look for. As experienced pilots have "die-hard" habits, getting used to new methods such as tactile cues can be difficult for them. With inexperienced pilots, there are not such habits yet so results given by them to same test could be different and comparing these could result in useful data.

- Using different cueing methods for different flight phases of the aircraft could be investigated. Such as hard stops in takeoff and landing while soft stops in flight for the same parameter. Passing the angle-of-attack at high altitude could be recoverable while stalling in landing or takeoff could result in accidents.
- In this work, both angle-of-attack and load factor parameters were connected to the same cueing method. As some limit parameters allow overshoots while others should not be passed in any case, applying different cueing methods for different parameters could further improve the envelope protection while attaining more control over the aircraft.

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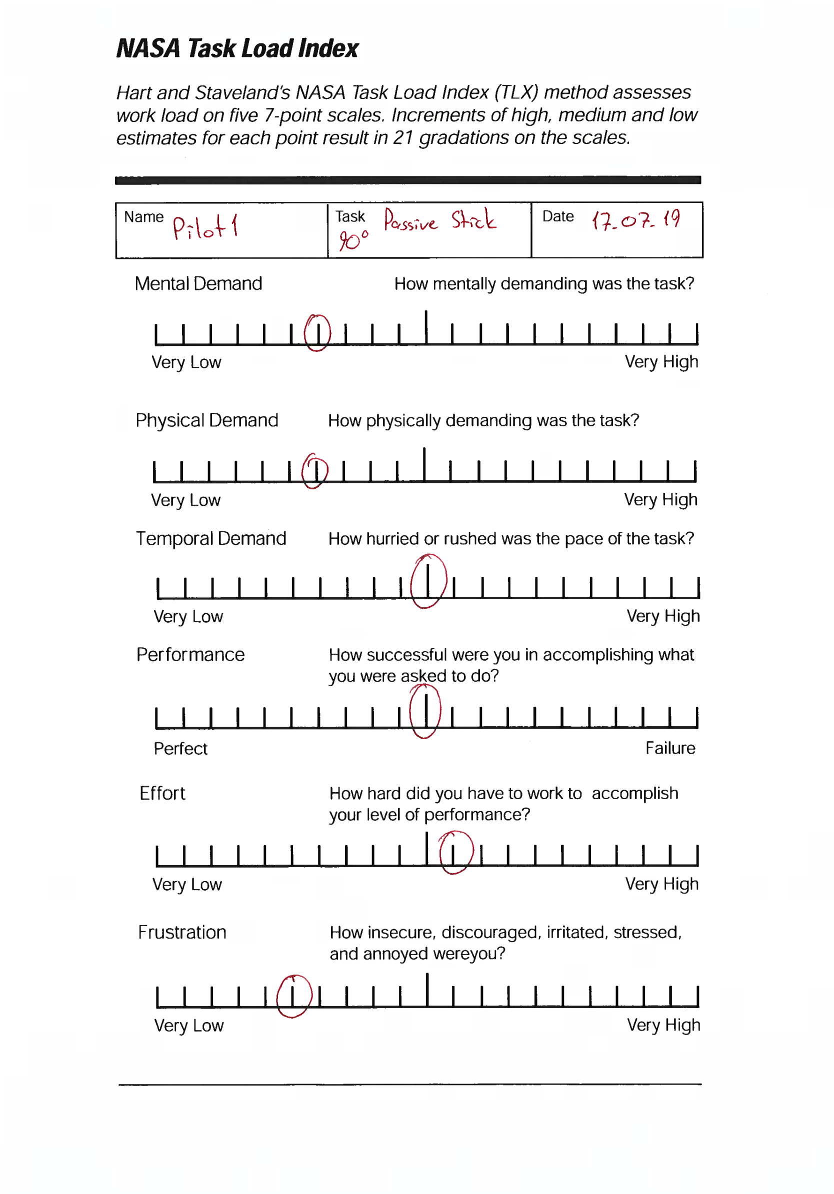
APPENDIX A

STATISTICAL DATA GATHERED FROM PILOTS

In this appendix, the grades given by pilots to the NASA-TLX rating questionnaires are presented. These data are used to compare different tactile cueing methods and generate the tables shown in "Piloted Simulations" subsection under Chapter 3. Figure A.1 to Figure A.8. Figure A.9 to Figure A.16 are grades given by Pilot 2 and Figure A.17 to Figure A.24 are grades given by Pilot 3.



NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name Pilot 1	Task Passive Stick 90°	Date 17.07.19

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

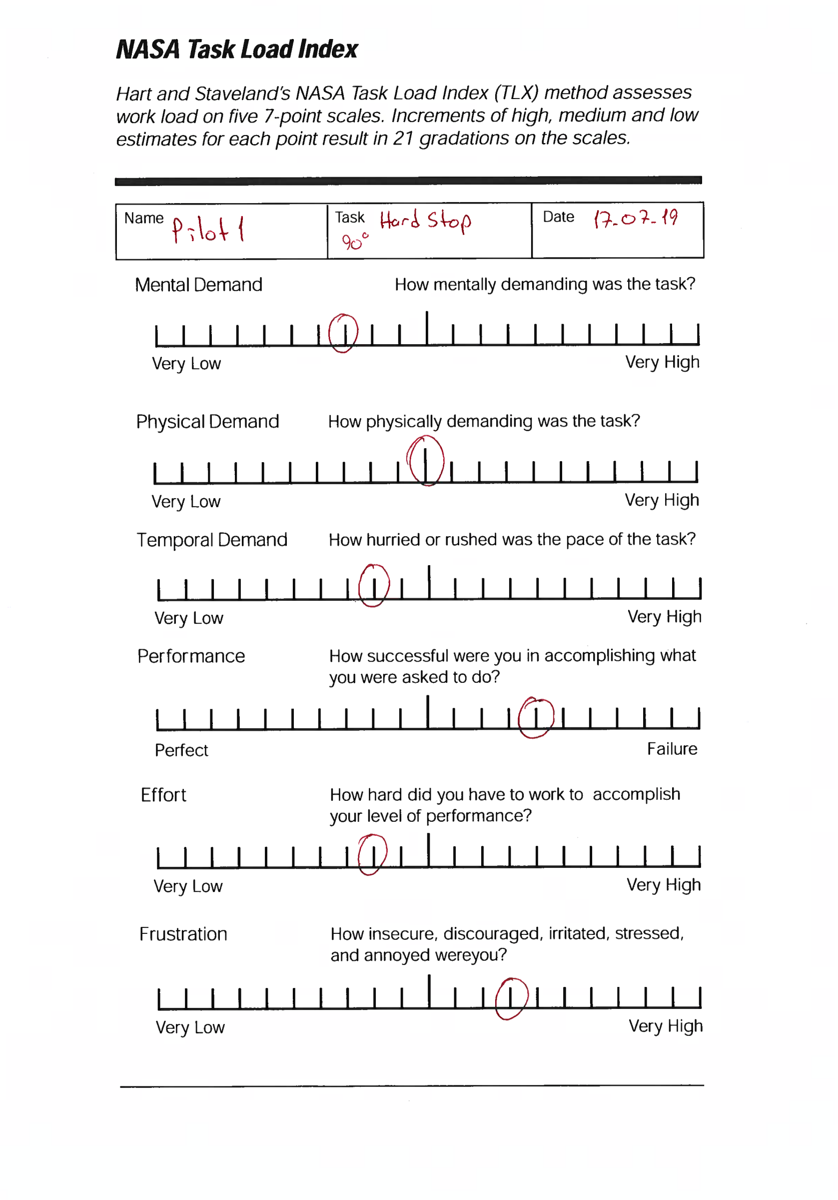
Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

Figure A.1: Pilot 1 passive stick TLX grades



NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name Pilot 1	Task Hard Stop 90°	Date 17.07.19

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

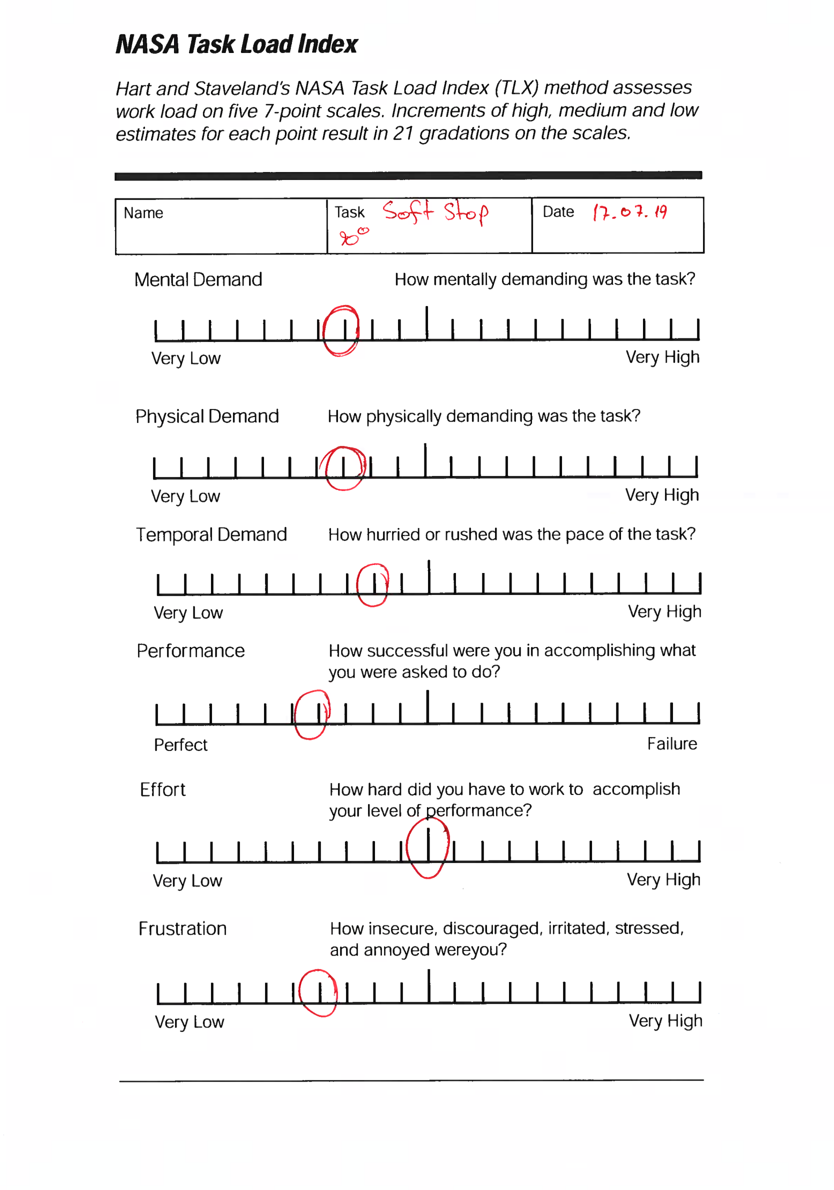
Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

Figure A.2: Pilot 1 hard stop grades



NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name	Task Soft Stop 80°	Date 17.07.19

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

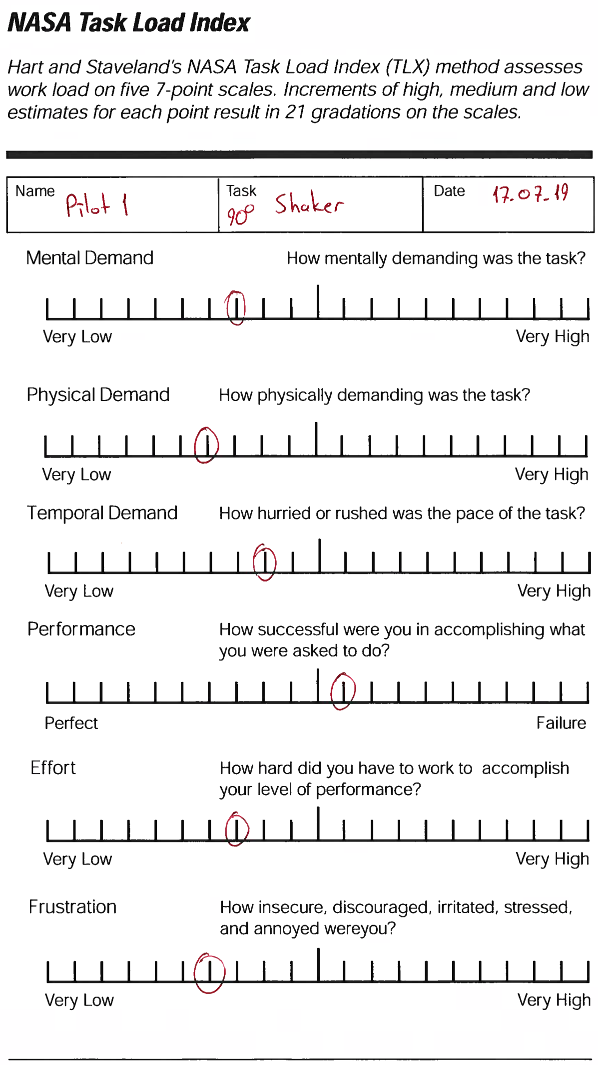
Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

Figure A.3: Pilot 1 soft stop TLX grades



NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name Pilot 1	Task 90° Shaker	Date 17.07.19

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

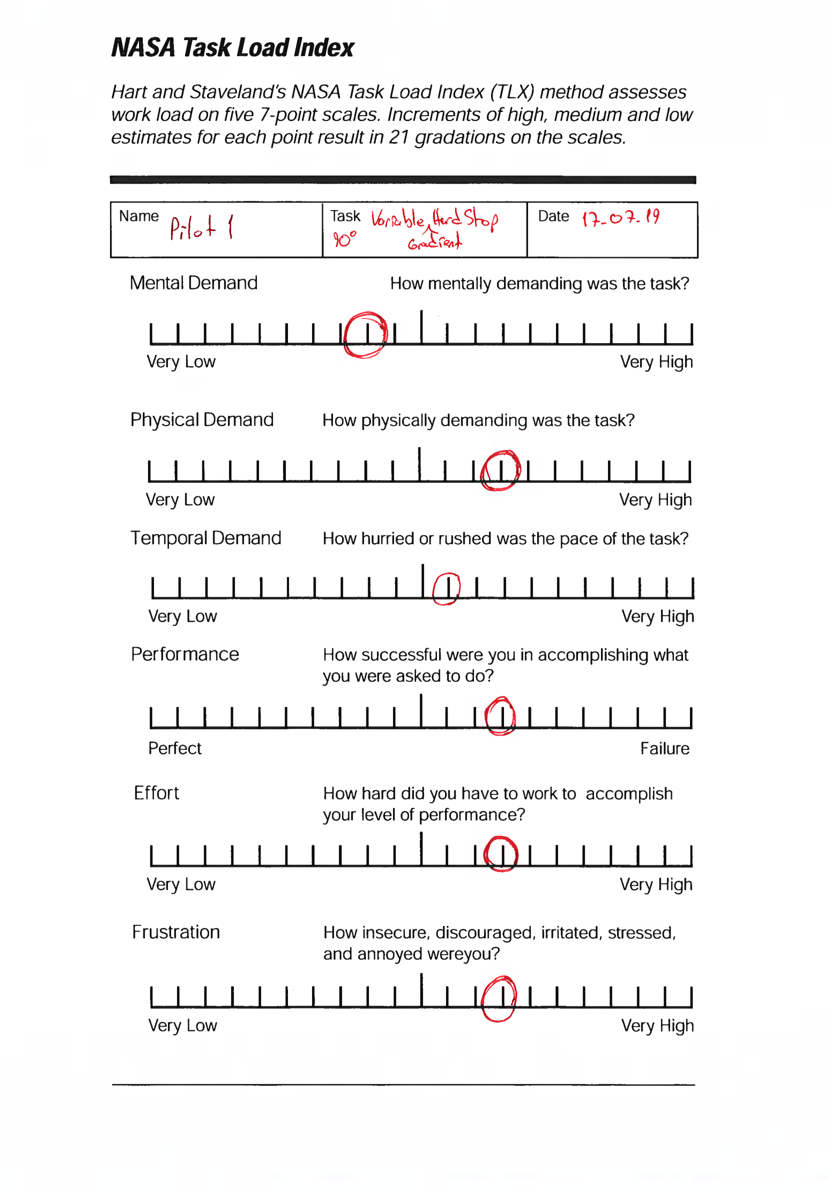
Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

Figure A.4: Pilot 1 shaker TLX grades



NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name Pilot 1	Task Variable Gradient Hard Stop 90°	Date 17-07-19

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

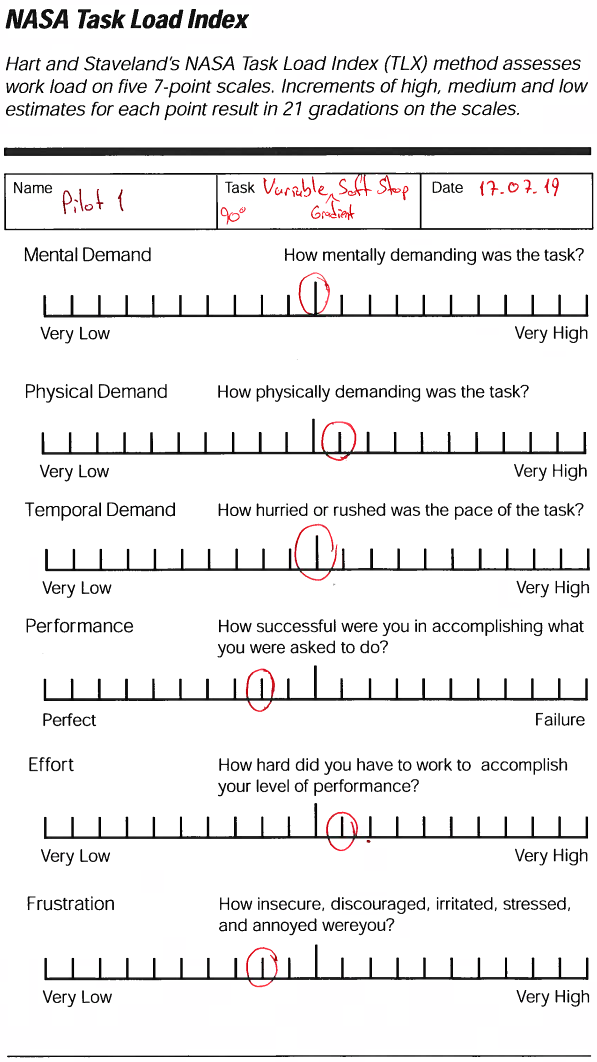
Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

Figure A.5: Pilot 1 variable gradient hard stop TLX grades



NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name Pilot 1	Task Variable Gradient Soft Stop 90°	Date 17.07.19

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

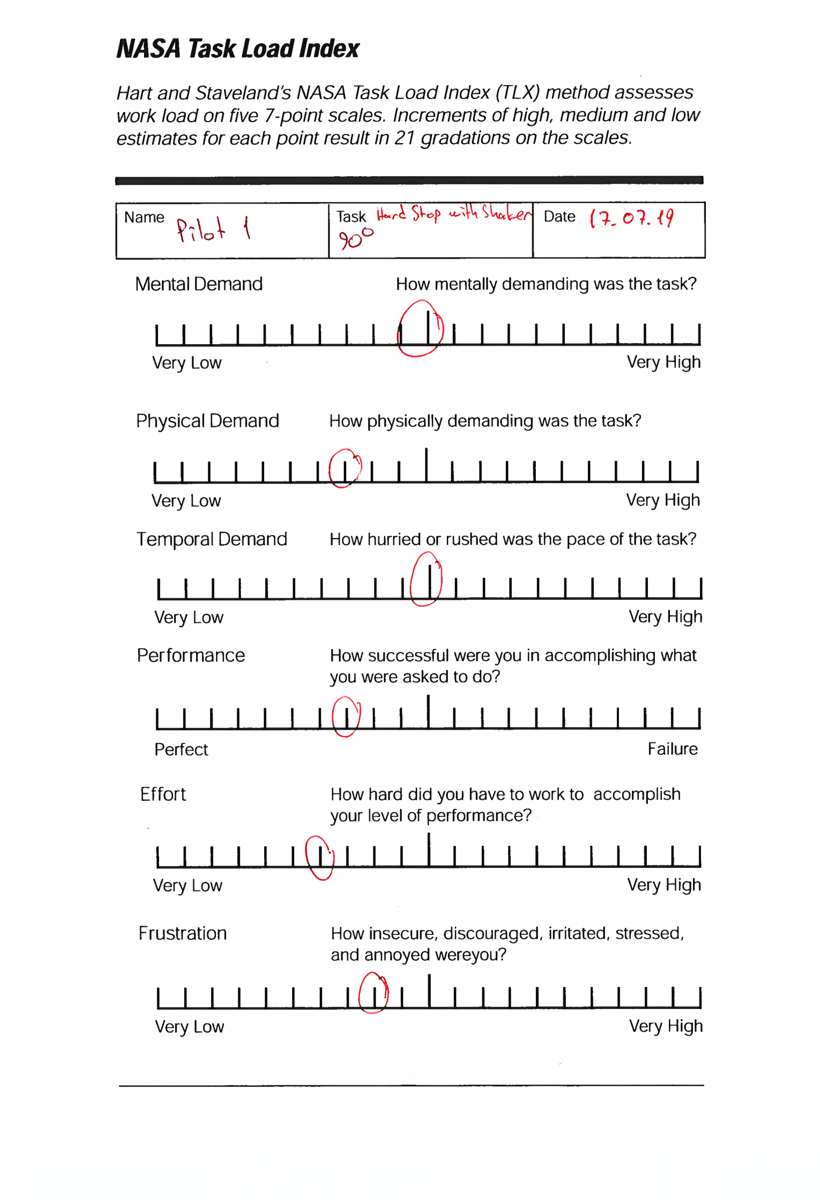
Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

Figure A.6: Pilot 1 variable gradient soft stop TLX grades



NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name Pilot 1	Task Hard Stop with Shaker 90°	Date 17.07.19

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

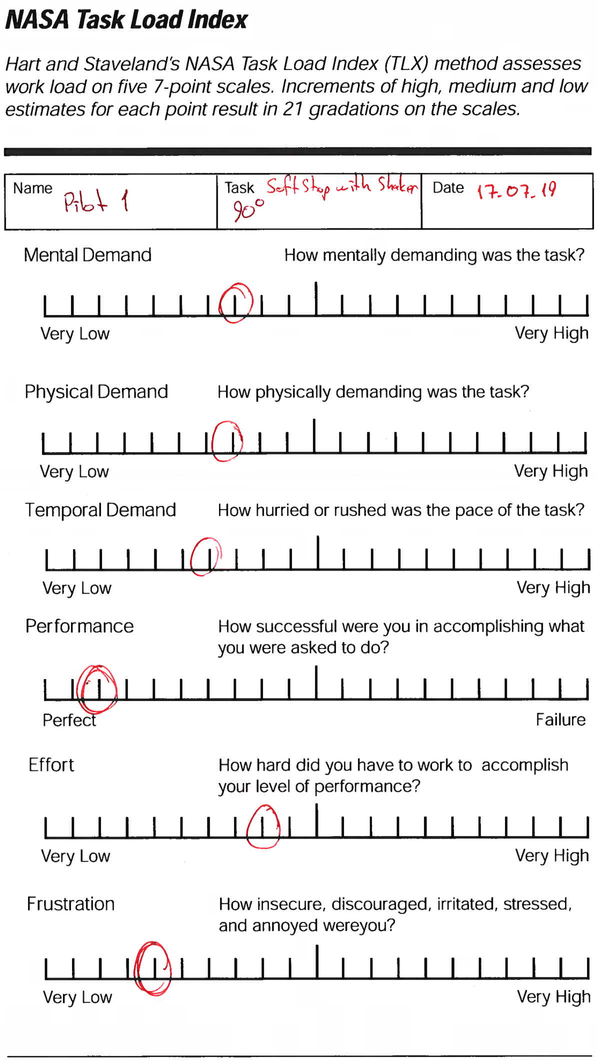
Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

Figure A.7: Pilot 1 hard stop with shaker TLX grades



NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name	Task	Date
Pilot 1	Soft Stop with Shaker 90°	17.07.19

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

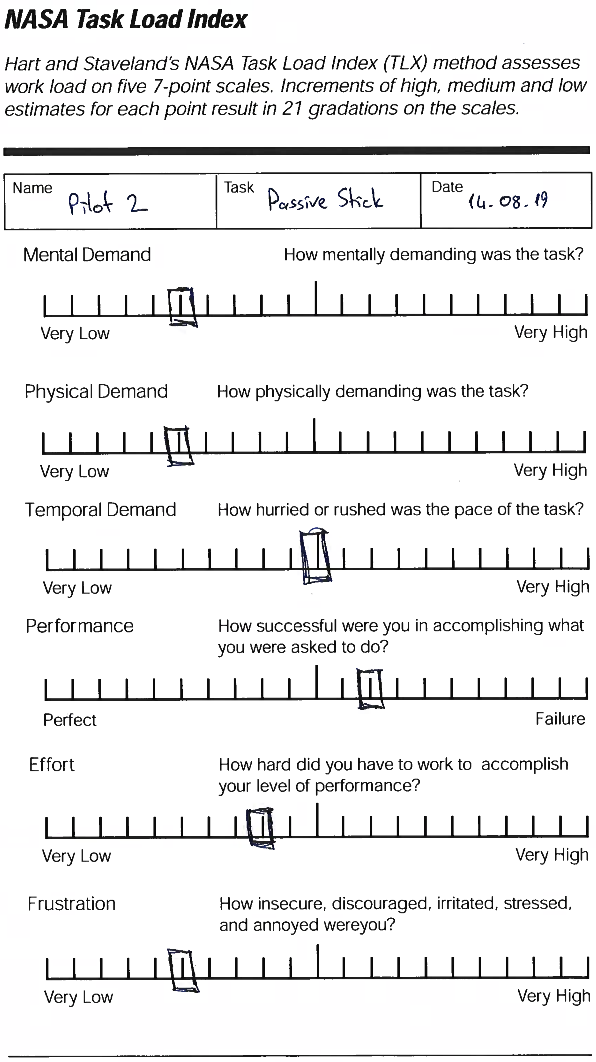
Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

Figure A.8: Pilot 1 soft stop with shaker TLX grades



NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name Pilot 2	Task Passive Stick	Date 14.08.19

Mental Demand — How mentally demanding was the task?
Very Low — Very High

Physical Demand — How physically demanding was the task?
Very Low — Very High

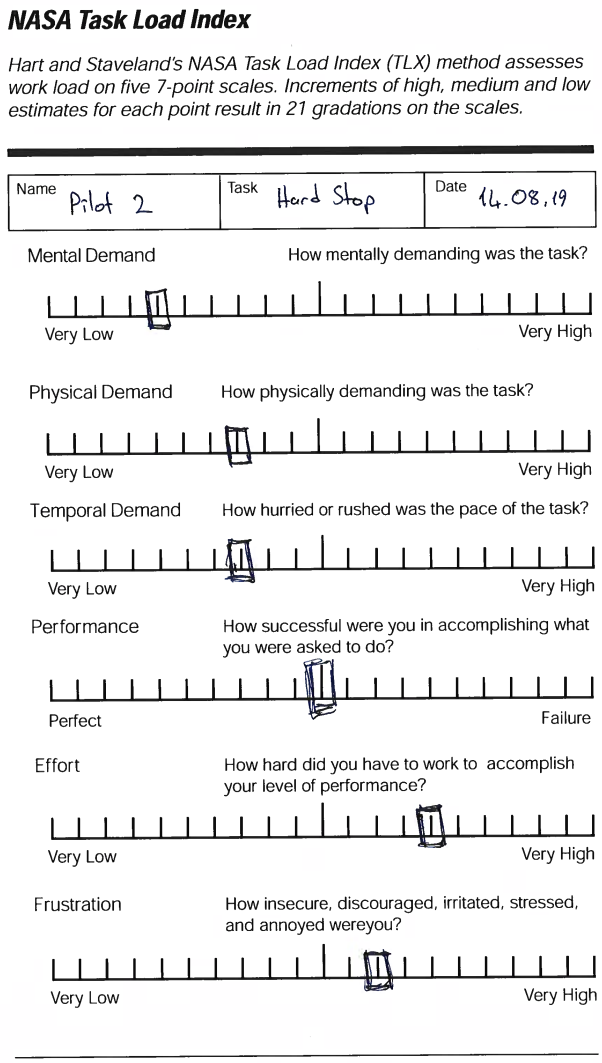
Temporal Demand — How hurried or rushed was the pace of the task?
Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?
Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?
Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?
Very Low — Very High

Figure A.9: Pilot 2 passive stick TLX grades



NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name Pilot 2	Task Hard Stop	Date 14.08.19

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

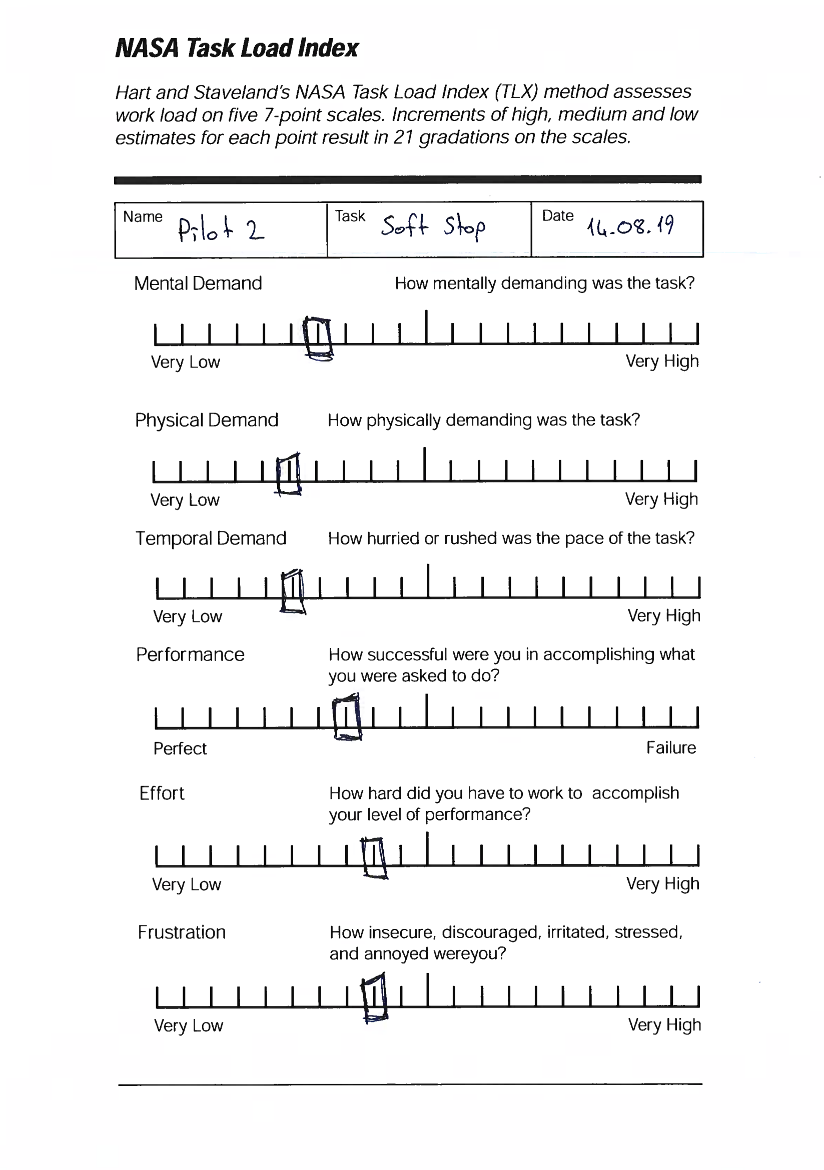
Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

Figure A.10: Pilot 2 hard stop grades



NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name Pilot 2	Task Soft Stop	Date 14.08.19

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

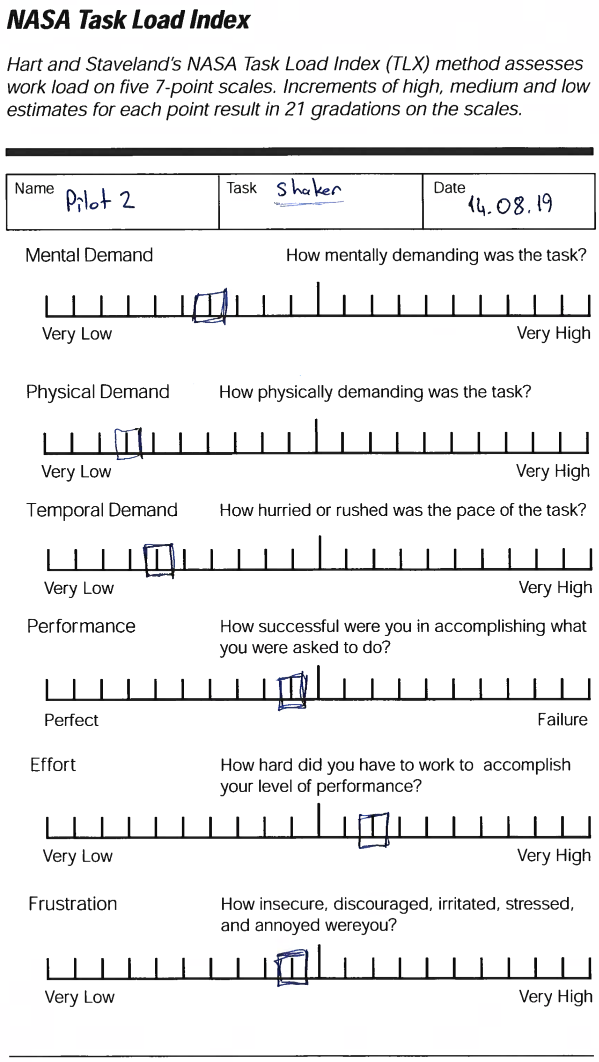
Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

Figure A.11: Pilot 2 soft stop TLX grades



NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name Pilot 2	Task Shaker	Date 14.08.19

Mental Demand — How mentally demanding was the task?
Very Low — Very High

Physical Demand — How physically demanding was the task?
Very Low — Very High

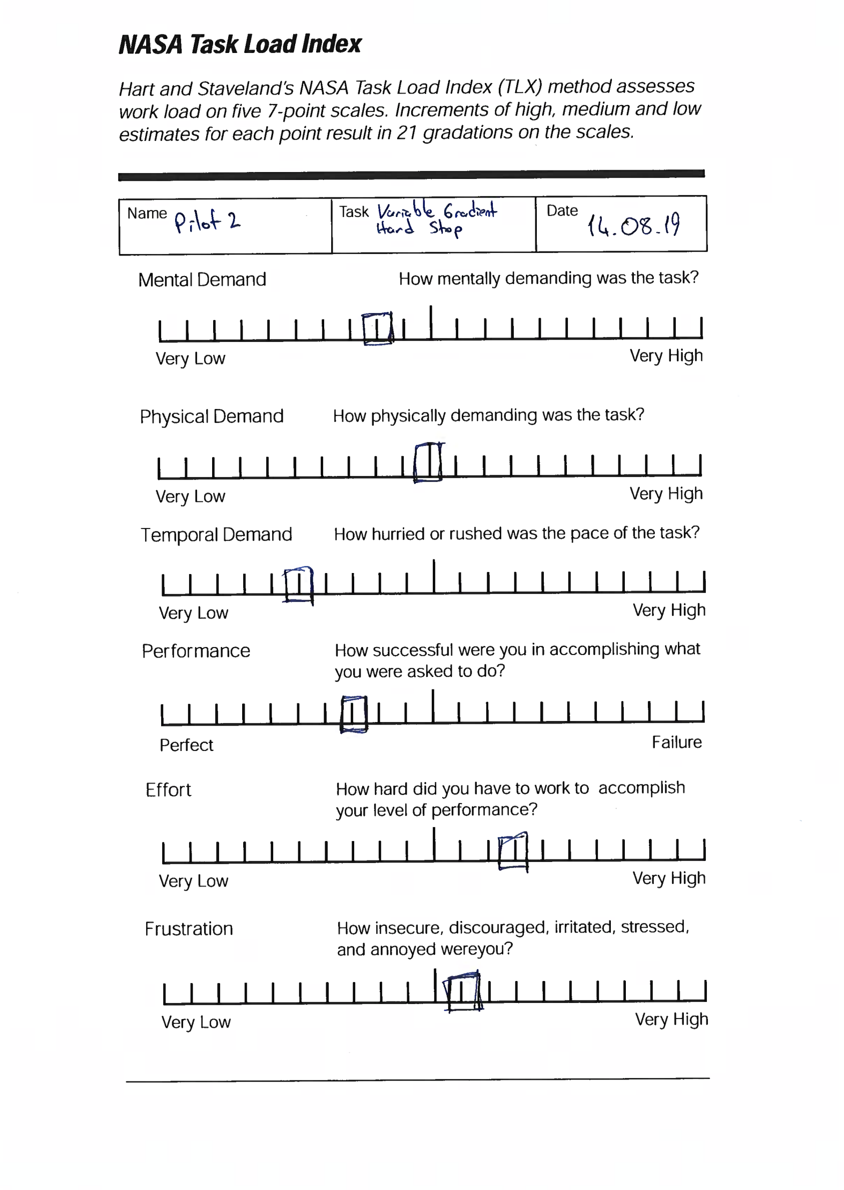
Temporal Demand — How hurried or rushed was the pace of the task?
Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?
Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?
Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?
Very Low — Very High

Figure A.12: Pilot 2 shaker TLX grades



NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name Pilot 2	Task Variable Gradient Hard Stop	Date 14.08.19

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

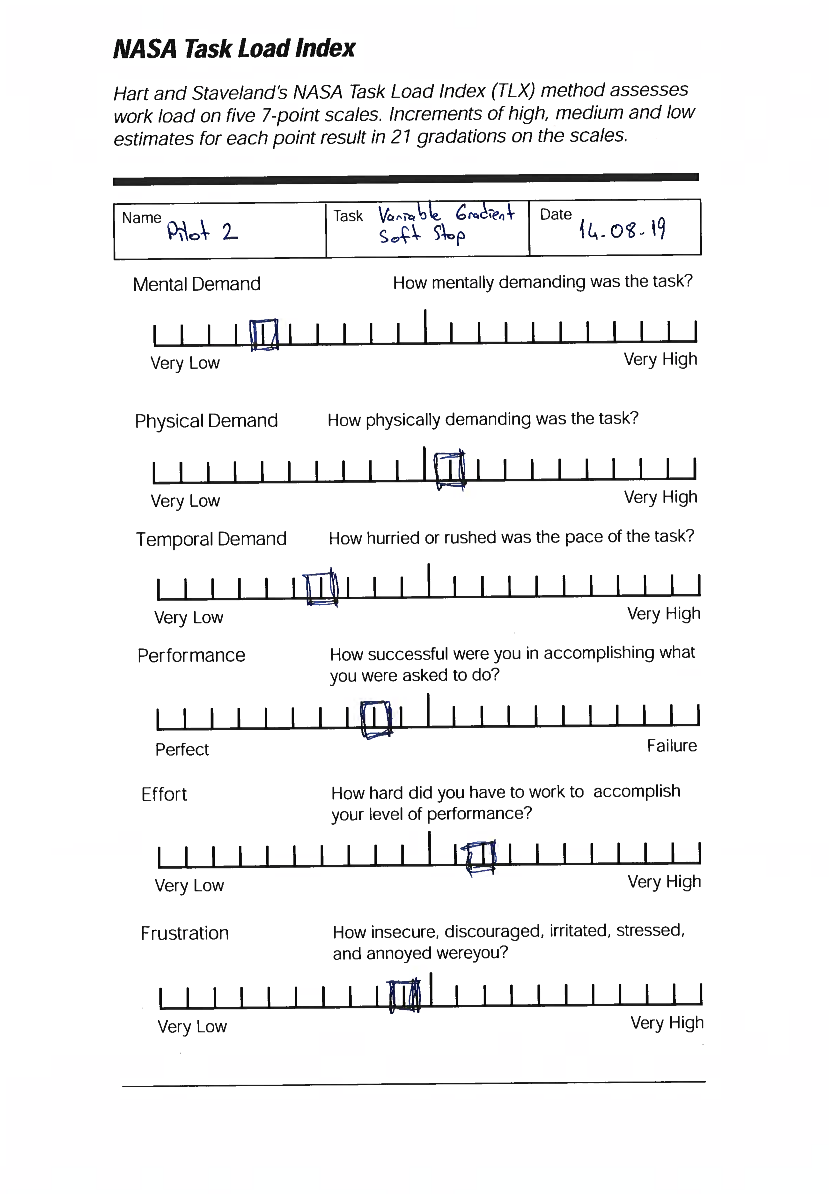
Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

Figure A.13: Pilot 2 variable gradient hard stop TLX grades



NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name Pilot 2	Task Variable Gradient Soft Stop	Date 14.08.19

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

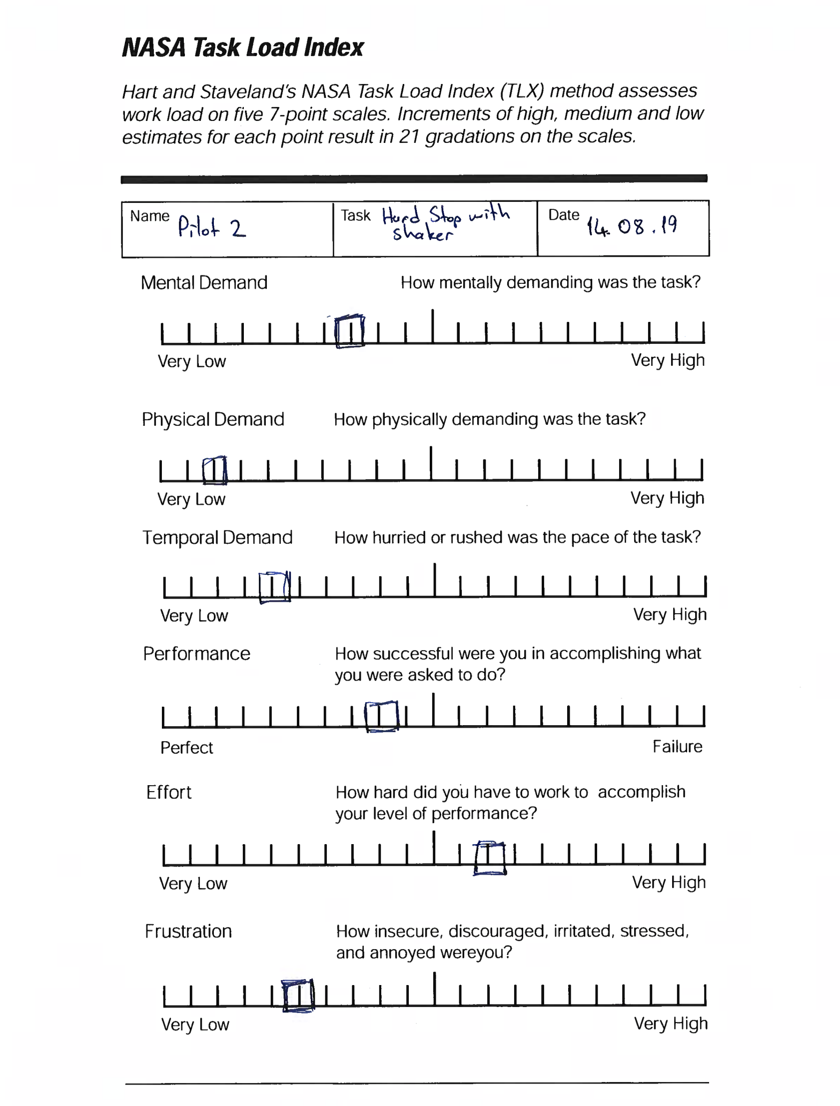
Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

Figure A.14: Pilot 2 variable gradient soft stop TLX grades



NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name Pilot 2	Task Hard Stop with shaker	Date 14.08.19

Mental Demand — How mentally demanding was the task?
Very Low — Very High

Physical Demand — How physically demanding was the task?
Very Low — Very High

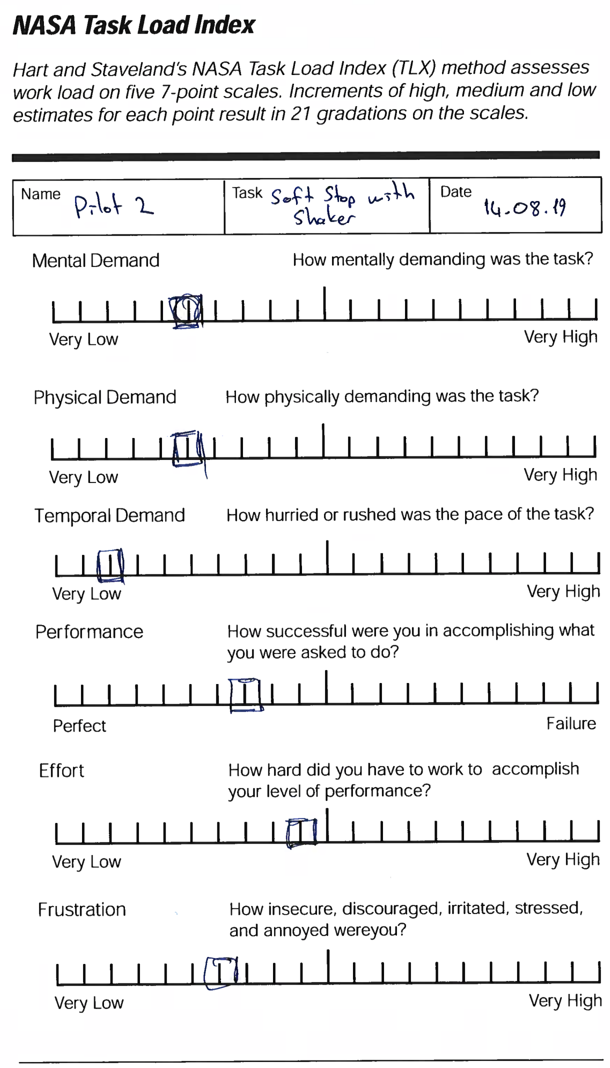
Temporal Demand — How hurried or rushed was the pace of the task?
Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?
Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?
Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?
Very Low — Very High

Figure A.15: Pilot 2 hard stop with shaker TLX grades


NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name Pilot 2	Task Soft Stop with Shaker	Date 14.08.19

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

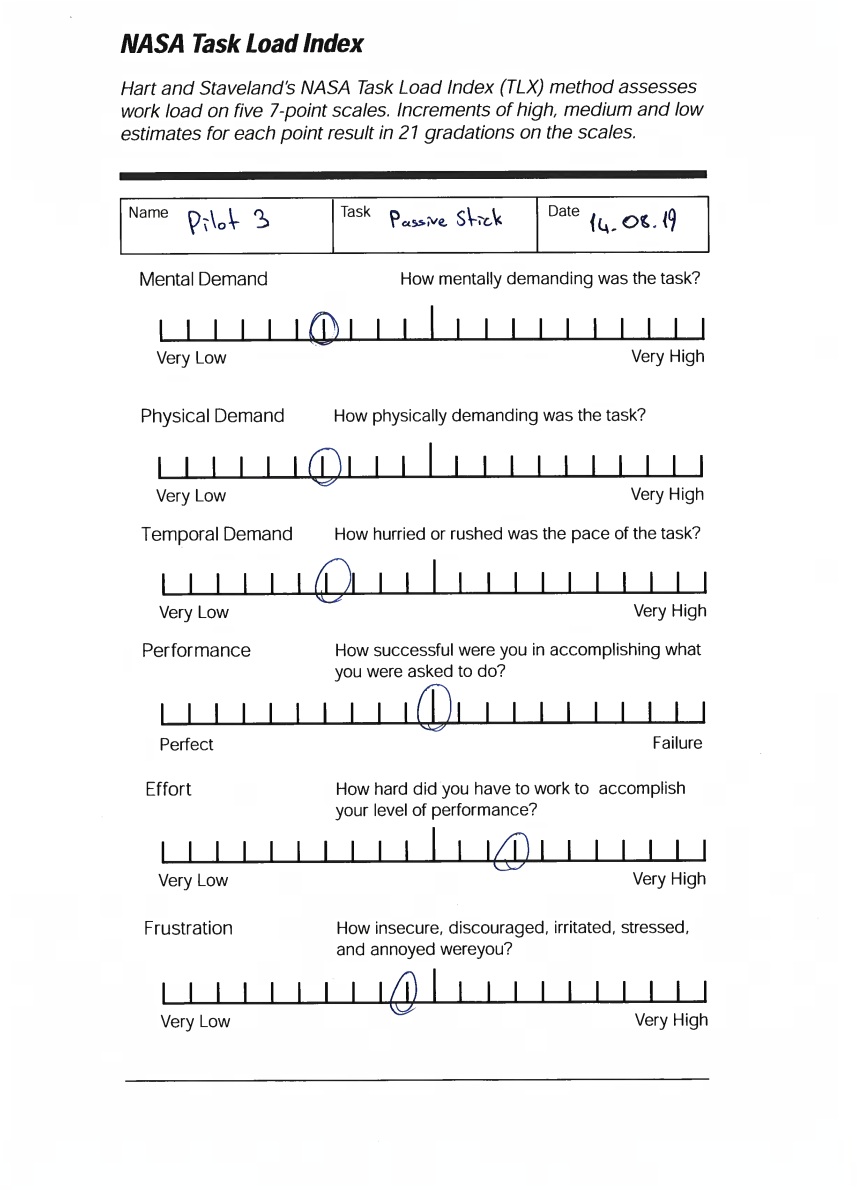
Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

Figure A.16: Pilot 2 soft stop with shaker TLX grades



NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name Pilot 3	Task Passive Stick	Date 14.08.19

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

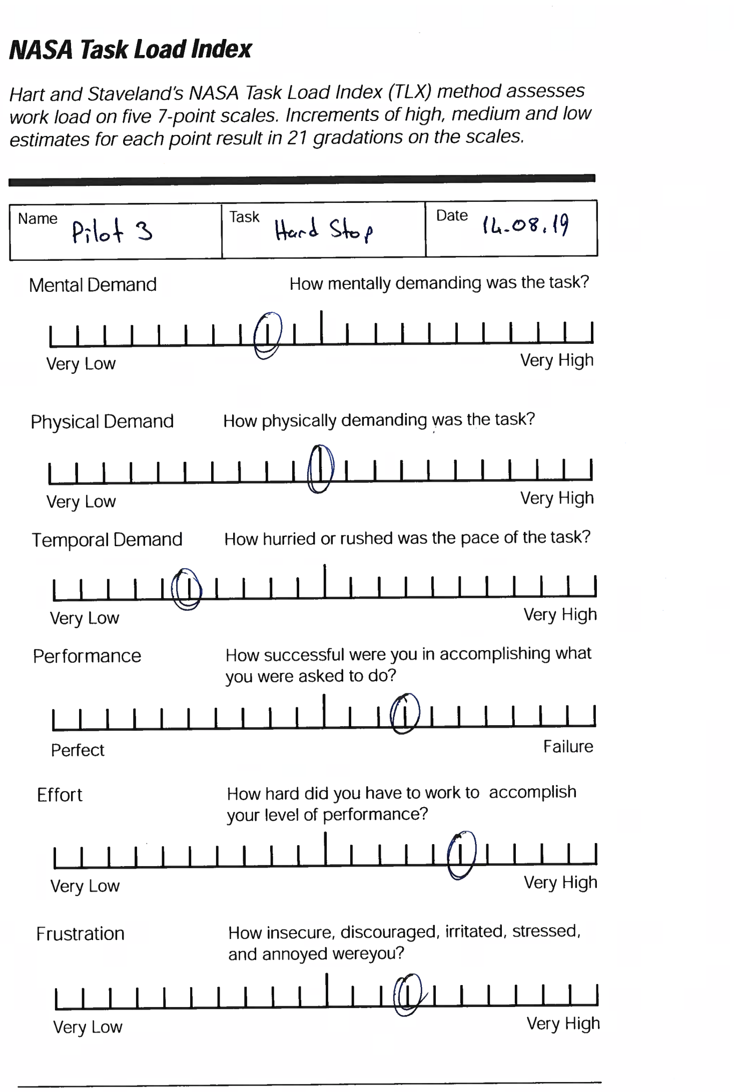
Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

Figure A.17: Pilot 3 passive stick TLX grades



NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name Pilot 3	Task Hard Stop	Date 14.08.19

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

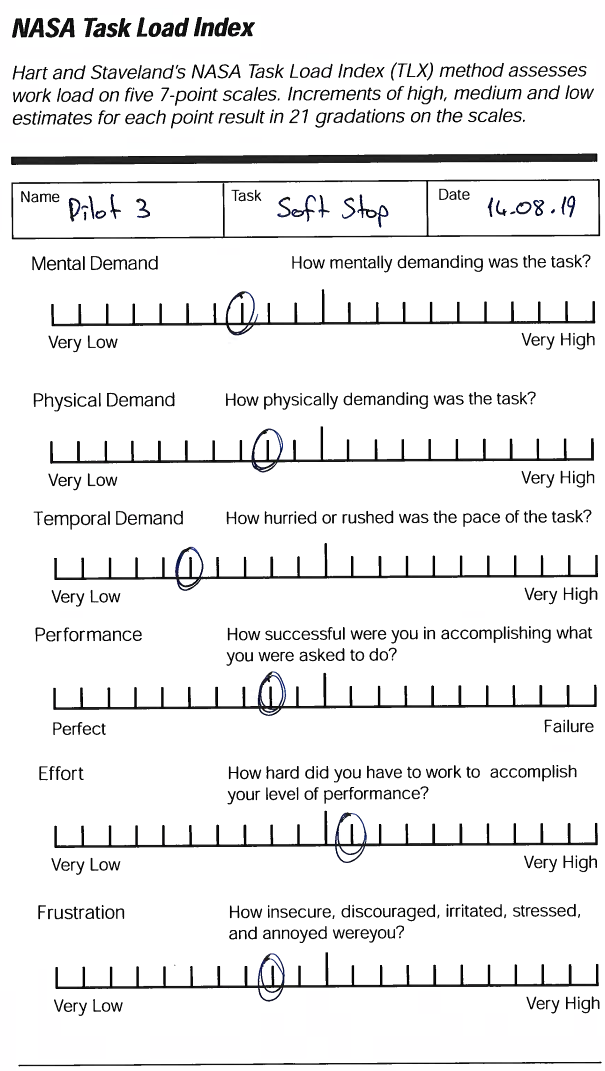
Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

Figure A.18: Pilot 3 hard stop grades



NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name Pilot 3	Task Soft Stop	Date 14.08.19

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

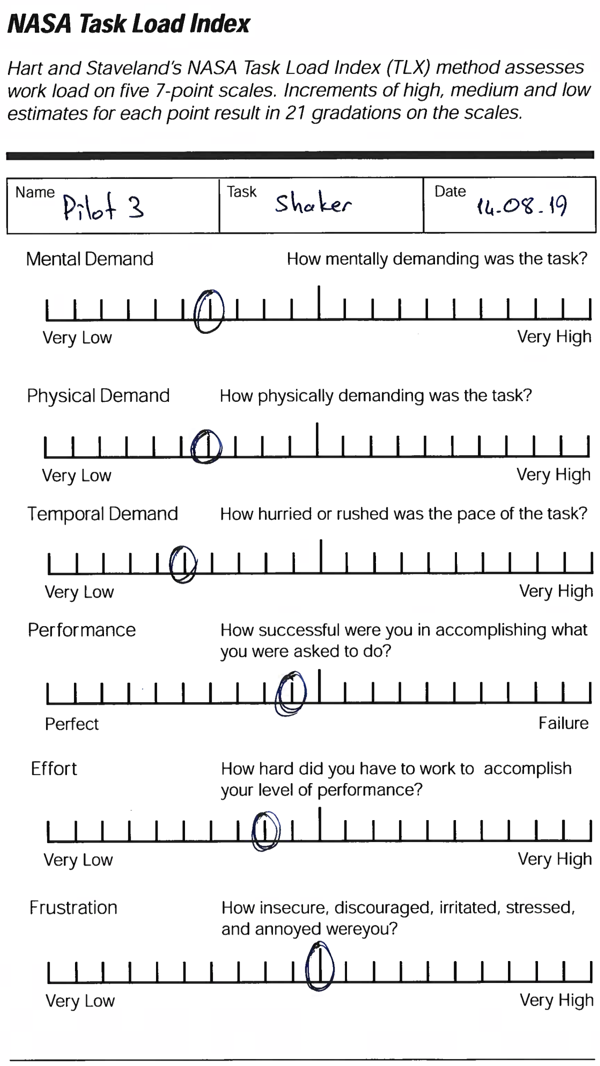
Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

Figure A.19: Pilot 3 soft stop TLX grades


NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name Pilot 3	Task Shaker	Date 14.08.19

Mental Demand — How mentally demanding was the task?
Very Low — Very High

Physical Demand — How physically demanding was the task?
Very Low — Very High

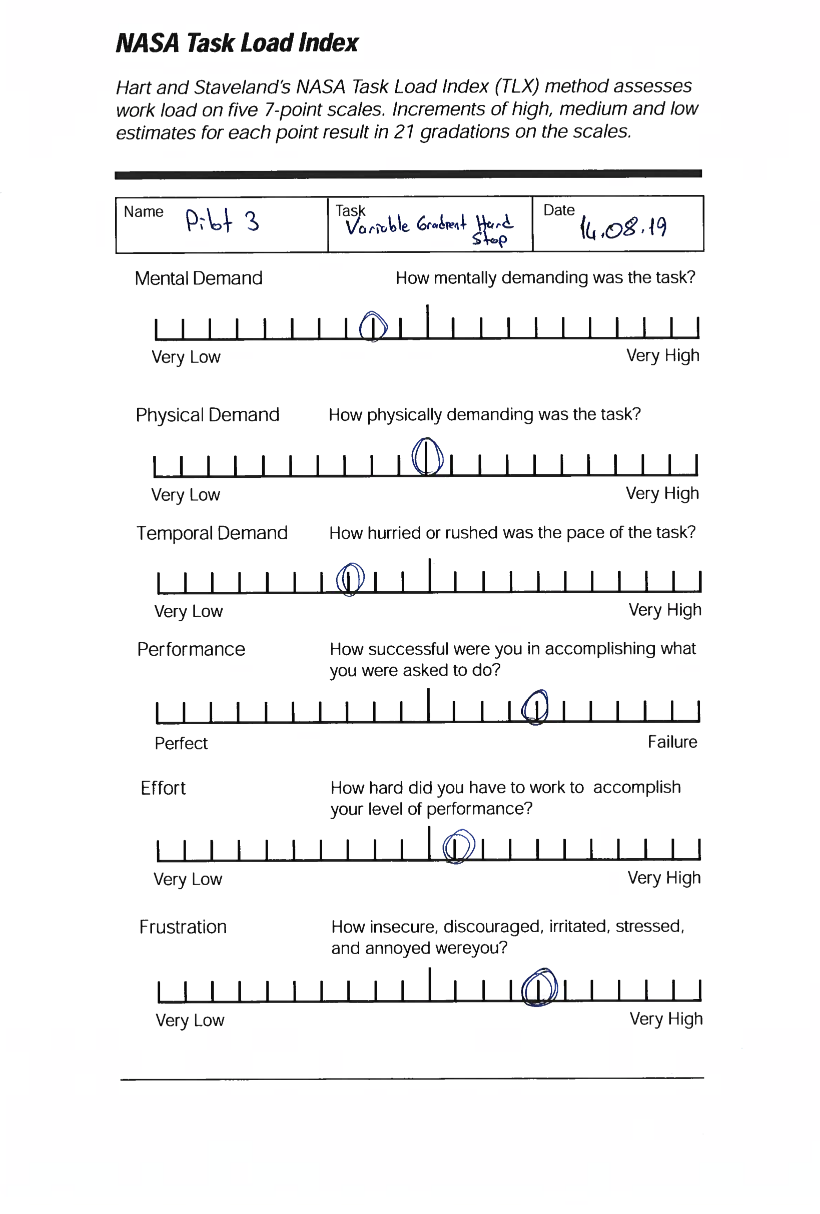
Temporal Demand — How hurried or rushed was the pace of the task?
Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?
Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?
Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?
Very Low — Very High

Figure A.20: Pilot 3 shaker TLX grades



NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name Pilot 3	Task Variable Gradient Hard Stop	Date 14.08.19

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

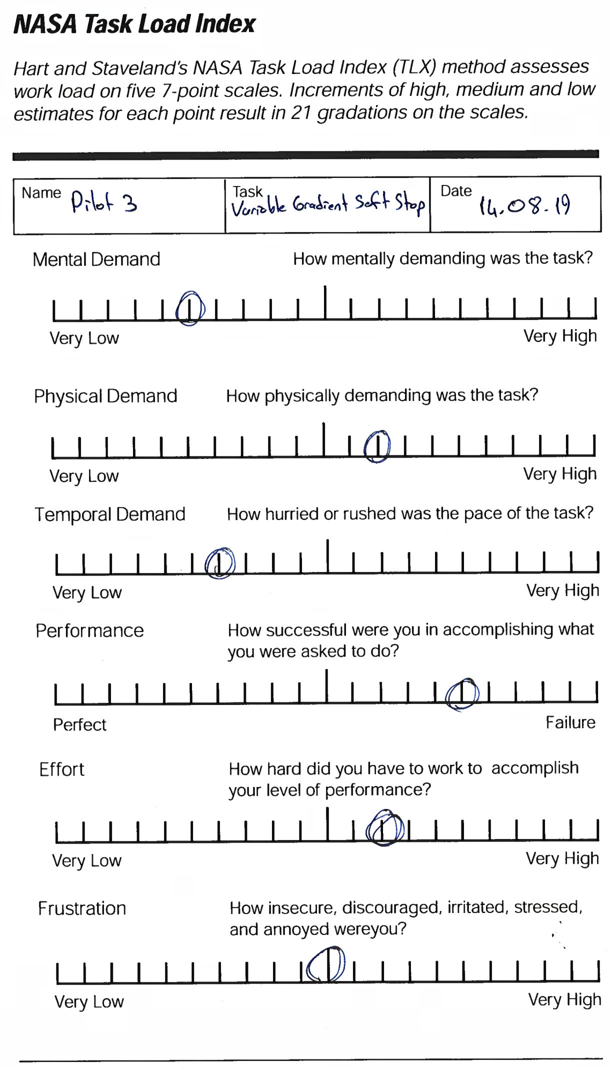
Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

Figure A.21: Pilot 3 variable gradient hard stop TLX grades



NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name Pilot 3	Task Variable Gradient Soft Stop	Date 14.08.19

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

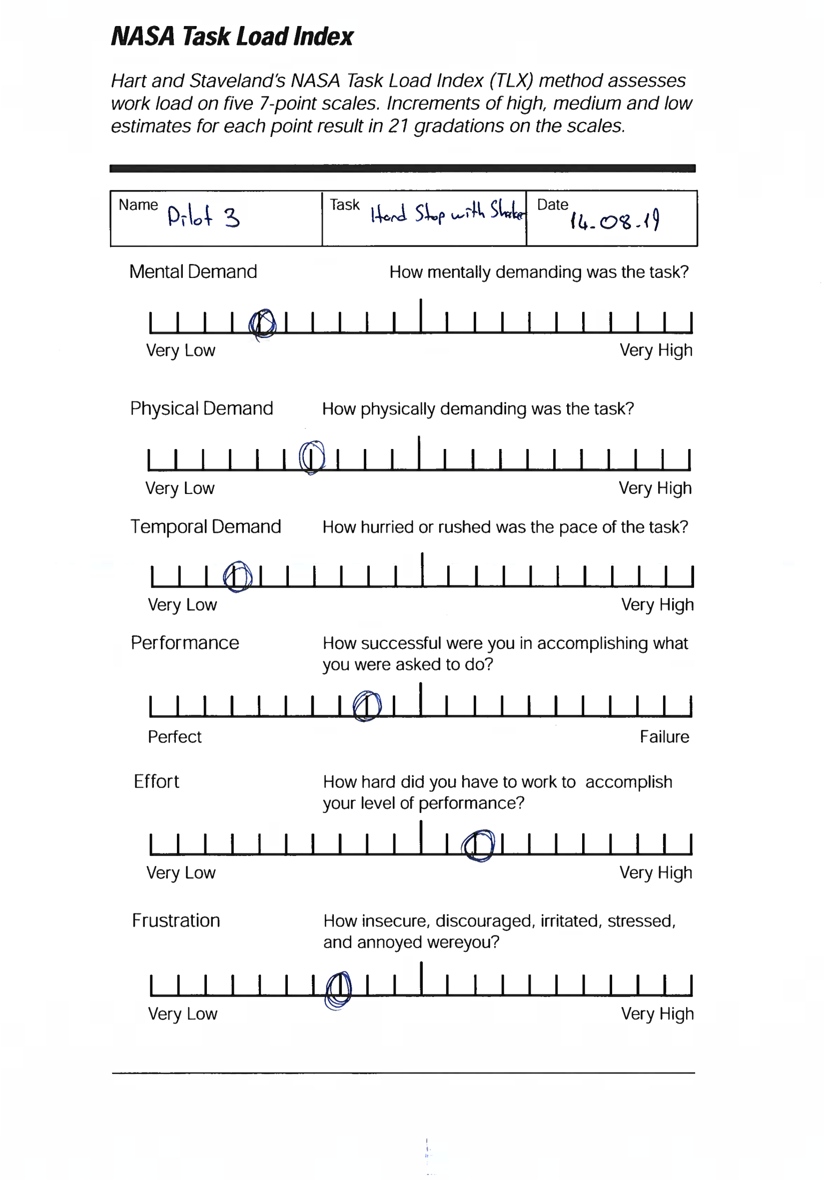
Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

Figure A.22: Pilot 3 variable gradient soft stop TLX grades



NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name Pilot 3	Task Hard Stop with Shaker	Date 14.08.19

Mental Demand — How mentally demanding was the task?
Very Low — Very High

Physical Demand — How physically demanding was the task?
Very Low — Very High

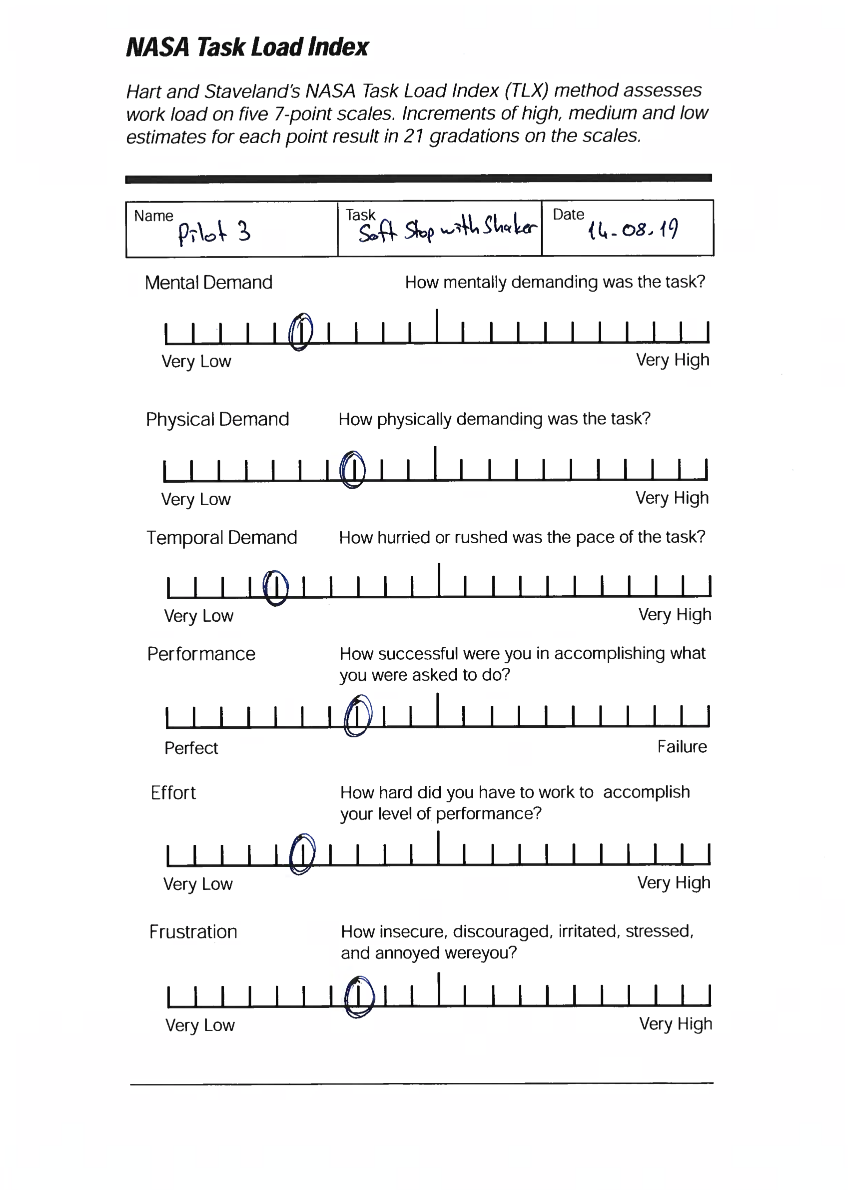
Temporal Demand — How hurried or rushed was the pace of the task?
Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?
Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?
Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?
Very Low — Very High

Figure A.23: Pilot 3 hard stop with shaker TLX grades



NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name	Task	Date
Pilot 3	Soft Stop with Shaker	14-08-19

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

Figure A.24: Pilot 3 soft stop with shaker TLX grades