# EFFECTS OF ERRORS ON TRANSFER OF AIRCRAFT FLIGHT TRAINING

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**Abstract:** A simplified analytical model for the Beech Bonanza model E33A aircraft with retractable undercarriage was used to determine the effect of tolerances on forced landings. It was found that the effect of the tolerances is highly sensitive on the nature of the manoeuvre flown and that in some cases negative transfer of training may be induced by the tolerances. An investigation on the effect vertical thermal disturbances on a forced landing manoeuvre was also carried out. The results show that the vertical disturbances are highly sensitive to the nature of the manoeuvre flown and they are therefore important to flight simulation. This analysis demonstrates the importance of analyses of vertical disturbances to flight simulation and the consideration of such requirements within the context of particular manoeuvres to be flown, as in some cases, negative transfer of training may be induced by the vertical disturbances. The vertical disturbances sensitivity analysis shows that a simulator may incur significant errors in the task of handling an engine failure after takeoff for a single engine aircraft. This raises the question of the ability to use simulators to train pilots aptly for engine failure after take-off using the tolerances as specified in current regulations since the resultant errors are manoeuvre dependent. A forced landing trajectory optimisation was carried out using Genetic Algorithm (GA). Simulations were carried out for a time averaged thermal disturbances at three test locations. The results show that certain pre-selected touchdown locations are more susceptible to horizontal wind. The results for the forced landing manoeuvre to a pre-selected location found results with minimal distance error.

## 1 INTRODUCTION

The advancement of computer technology has made it possible for increasing the role of flight simulators for initial pilot training for both civil and military pilots. It has also enabled pilots to be trained in more complicated and dangerous manoeuvres in emergency procedures without endangering the pilots' lives, and in developing new methods of achieving operational objectives. The costs of modern aircraft and the increasing complexity of the operating environment are placing more demands on flight simulators to provide more types of training as well as a safe and improved learning environment. Flight simulations provide researchers with the ability to identify and define specific human capabilities and limitations in man/systems. They are also used to explore interrelationships between machines and humans under various configurations and environments. Flight simulators are used for three primary purposes (a) in training individual pilots and other crewmembers, (b) to support initial training of pilots, navigators and systems operators in the Air Force, the Navy and the Army as well as civilian pilots from civilian colleges, universities and flying schools and (c) to train pilots in skills and procedures that they could never practise in a real world setting [1].

To date, flight simulators have been widely used by commercial airlines for pilot training. They have become so sophisticated that the highest approved category of simulations allows zero flight time training for commercial airline pilots converting to a new aircraft type. Flight simulations for military use are far more intricate and agile than those for commercial airlines. Despite the advancements, flight simulations are still not widely used in military training. This is because the human perceptual and learning processes involved are still not well enough understood to permit the completely accurate prediction of the levels of information or fidelity required to ensure significant levels of positive transfer of training in many important tasks. The objective determination of the ability of simulator training to transfer to the aircraft has always been recognised as a fundamental problem. This has resulted in a great deal of effort being devoted to designing simulators to provide as many of the characteristics assumed to contribute to transfer as possible [2].

Recent advances in aircraft technology are also creating new ways of operating aircraft. For example, gas turbine engines are now so reliable that a number of countries including Australia are approving the use of single engine gas turbine aircraft for regular public transport. This creates new opportunities and challenges for the simulation industry. One approach to flight simulator development is to attempt to replicate the entire real world scenarios. This method is limited by the physical hardware e.g. constraints of computers, visual reproductions and input devices. The other approach is to define the supporting tasks such as delay compensation, visual fidelity and motion in order to replicate the real world scenarios. An issue associated with this approach is the effect the supporting tasks have on the learning transfer from flight simulation training to real life performance and if there exists a relevant performance correlation between training on a flight simulator and real life performance.

The application of flight simulators for initial pilot training for both civil and military pilots is still relatively under exploited. For example, training of ab-initio pilots in emergencies such as forced landings is still carried out in aircraft. Similarly, almost all training of combat manoeuvres for military pilots is also carried out in aircraft. The issues involved in conducting such training in simulators are not well developed in the literature. The basic piloting tasks for the approach and landing are similar for most aircraft and these tasks can be as demanding as any of the complete mission of an aircraft. As an example, this study considered the trajectory that a pilot must fly after an engine failure and how pilots could be trained for this manoeuvre in a simulator. It raises some issues for training pilots to fly forced landings and examines the impact that these issues may have on the design of simulators for such training. Although a high fidelity airplane model can be used to model the aircraft performance but intrinsic tolerance and errors which are inherent to the model will not provide perfect solutions.

Simulator manufacturers assume that flight simulators can train pilots appropriately but how accurate are the training when even with the advancement of technology, a flight simulator cannot perfectly represent a particular aircraft in all aspects. For example, the mathematical model of the aircraft is never fully accurate, the motion and visual systems have physical limitations that make the full representation of the sensation of flying always less than perfect. The time delay in flight simulation which is also known as transport delay, consists of two components: the constant inherent delay due to processing time from the input device to the visual image or transmission over the physical distance and the variable delay due to traffic or congestion over a network. The inherent transport delay problem in flight simulators may cause the pilot to fly a totally different manoeuvre in real life than in a flight simulator or to even react differently. This raises the issue on the appropriate transfer of training from flight simulators.

Therefore, an analysis on the effects artefact such as delay has on a forced landing manoeuvre was also carried out. The effects of delay were represented in a form of wind disturbances in a forced landing analysis. For example, consider the case when a pilot has picked an aiming point to land but due to some blurred vision, uncertainties in distance and elevation may affect the pilot's reaction or judgment in landing the airplane. The uncertainties may be present in a form of wind disturbances. This difference in judgment or the presence of errors and uncertainties are related to the study of transfer of training from flight simulators since the pilot may manoeuvre the aircraft differently given the presence of uncertainties or errors in judgment. How much will the manoeuvre differ from some reference manoeuvre? Will the uncertainties affect the pilot so much so as for the pilot to fly a totally different manoeuvre?

## 2 SKILLS TRANSFER IN TRAINING

This section presents an overview of research and technical reports regarding flight simulations, transfer of training and skills transfer. Flight simulation encompasses a very broad range of technical areas. Therefore, only publications that are specifically related to the work contained within this study are provided. A brief review on the historical background, the efficiency and effectiveness of skill transfer from flight simulators, and some of the inherent problems associated with flight simulation, such as delay, are presented.

### 2.1 Flight Simulation

Flight simulations enable a user to experiment with various systems configurations and modes of operations without the need of building an actual system. A flight simulator uses mathematical expressions to describe the major characteristics of the system whose output represents the response to the control inputs and environmental effects. A mathematical model may also be used to represent the human-in-the-loop operator. However, the accuracy of the mathematical model may not be well known. Hence, it may require a complex system to estimate the relative value of the system configurations and characteristics. The most important role of the flight simulator is to train pilots, however they are also used for basic and applied research into establishing human capabilities and limitations, as well as to explore how humans and systems interact under various circumstances and conditions.

A brief history of flight simulation was compiled by [3] and pilot training has been considered of vital importance since the beginning of manned flight. The first synthetic flight training device, the Antoinette trainer, consisted of two half-sections of a barrel. Its motion was manually controlled by instructors in order to simulate the pitch and roll motion of an airplane, and the pilot was required to align the reference bar with the horizon using the device controls. Over time, following some trial and error experiments, improvements were made on the manual motion by replacing both the mechanical or electrical actuators that were linked to the training device controls. In 1930, Edwin Link patented the Link Trainer (also known as the blue box-link simulator) as shown in Figure 1. It was the most successful and well-known training device of this type. Advancements in flight simulations were made during World War II with the use of a differential analyser within an analogue computer to solve the airplane's equations of motion. In 1941, Telecommunications Research Establishment in Britain designed and built an electronic simulator that solved the aircraft equations of motion.

From the 1950's, progress in flight simulators continued to improve with the addition of cockpit motion systems and in 1964 research on flight simulator motion began at the Faculty of Aerospace Engineering of Delft University of Technology (DUT). With the introduction of three Degrees of Freedom (DOF) motion systems (roll, pitch and heave), this faculty developed flight simulators that used hydraulic actuators in hydrostatic bearings. The motion systems continued to improve and the first commercially available six DOF motion system was developed by LMT (Thompson CSF) in 1977. Visual systems were then added and the first Computer Generated Image (CGI) system for simulation was produced by the General Electric Company [1]. Since then, flight-training devices have improved tremendously and technology has been driving the development of Full Flight Simulators (FFS).

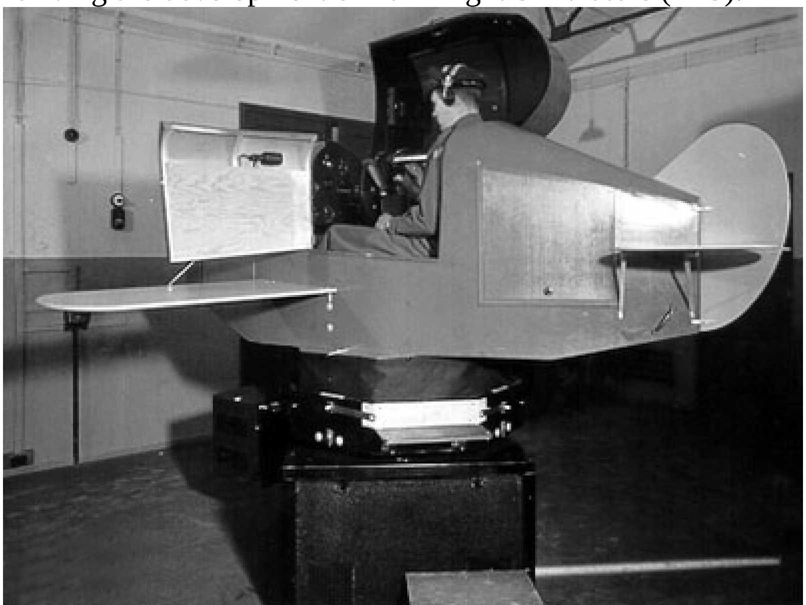


Figure 1: The Link Trainer[1]

Using flight simulators for pilot training has many advantages over training in a real airplane. For example, flight simulators are safer, more convenient, more flexible and more economical than training in a real airplane. They enable task specific training where additional skills can be acquired upon mastering basic skills, and they allow pilots to learn and practice critical, complex, and dangerous manoeuvres without risking lives. The flight simulators provide dedicated and effective learning and practice environment. They are particularly valuable in

[1] http://www.starksravings.com/linktrainer/linktrainer.htm

support of training for emergency procedures such as flying in adverse weather environment or at the edge of the flight envelope. [4] provided a list of nine training accidents where forty-five lives were lost and nine aircraft were destroyed. [5] compiled a list of flight accidents that resulted from military and civil flight training from 1965 – 1998 and there were more than 250 dead in 30 years. These training accidents could have been avoided had today's flight simulator existed and used.

The role of a flight simulator is to provide a tool with which student pilots learn how to fly and to demonstrate proficiency in flying an airplane. In flying a real airplane, the student pilot cannot afford the consequences of his or her incorrect control inputs. On the contrary, the use of a flight simulator allows the student pilot to experience improper pilot actions or even to fail in any given manoeuvre while eliminating potential catastrophic training accidents or risking their lives. It has been well accepted in the field of behavioural psychology that failure is a powerful feedback to human learning ability.

The growing role of the flight simulation for training, both civil and military, generates a potential market for more effective simulation systems. Another benefit in using flight simulators for flight training is in cost savings. In 1976, the use of flight simulators for training has an estimated saving of about $25 million per year in training cost for a particular airline by using an average of 26,000 flight simulator hours and for about 1100 hrs on an aircraft [6]. In 1972, the use of the UH-1 helicopter military flight simulators for training reduced actual flight hours from 116 hours to 26.5 hours, which translated to a saving of over $4,000 per student [1]. Some of the indirect saving in using flight simulators is the cost involved in the support of flying the actual airplane such as personnel and facilities needed to support flight operations, and in the wear and tear of the airplane. Student pilots also save time by using the flight simulator for training. For example, if students were training for a specific task such as a landing manoeuvre, the students would have to take-off and fly the circuit for the landing manoeuvre. In a flight simulator, the student pilots can virtually spend the entire practice session on the particular landing manoeuvre task. Currently, in the whole of Europe, only a handful of airports allow unrestricted training flights and the number is decreasing [5]. Hence, the demand for using flight simulators to train pilots is increasing.

Flight simulators are being used for training military and civilian transport pilots. In training civilian pilots, FFS has been recognized as an integral part of flight training from ab initio pilot training to advanced training including type conversion. The military use flight simulators for training specific tasks but they are mainly used for dedicated ongoing proficiency training. [7] discussed how the use of flight simulators has reduced the risks of military aircrew. Some of the applications of military flight simulators include training or practicing for evading air-to-air missiles, evading surface-to-air missiles, air-to-air combat, airborne surveillance and as mission simulator. These advanced follow-on training has driven the requirement for sophisticated simulation technology. The Air Education and Training Command of the U.S. Air Force conducted an analysis and evaluation of its flying program. It identified some current and future training problems and challenges that could be met by infusion of advanced modelling and simulation technologies [8].

### 2.2 Transfer of Training

The use of flight simulators to effectively train pilots has always been recognised as a fundamental problem. As a result, significant effort has been dedicated into designing flight simulators that will provide as many of the characteristics assumed to contribute to the transfer of training. It is very difficult to accurately predict the levels of information required to ensure significant levels of positive transfer of training since the human learning and perceptual processes are not well understood [1]. Full flight simulators have been driven by either the training establishment or the technological advances. It is important that the training community is aware of some of the inherent shortfalls that are associated in using flight simulators to train pilots. They should focus on the significant potential benefits while at the same time be aware of the current limitations of the commercially available flight simulators.

Some common questions in using flight simulators to train pilot are “How well do flight simulators train pilots?” “What constitutes learning?”, “What are the positive skill transfers and how do we recognize the potentially negative skills transfer?”, “What is expected from student pilots after a successful completion of the training?”. Despite the advancement of technology, a flight simulator cannot perfectly represent a particular aircraft in all aspects. For example, the mathematical model of an aircraft is never fully accurate, the motion and visual systems have physical limitations that make the full representation of the sensation of flying always less than perfect. The motion systems cannot fully replicate vertical motion, sustained linear and rotational accelerations as present in the roll, pitch, and yaw accelerations, and as well as in the normal load factor “g’s” but a certain level of fidelity may be achieved albeit at high cost. Pilots have to be aware of the limitations of sensory feedbacks that are provided and not to rely on them completely.

Flight simulators are not designed to simulate the whole spectrum of flight operation and therefore caution should be observed when using flight simulators out of the “normal operating envelope”, e.g. the simulation to accurately teach a pilot to recover from post stall or unusual attitudes/upset manoeuvres or engine failures after take-off. A potential improper application of flight simulators is in accident investigation. The National Travel Safety Board (NTSB) has cautioned that the use of flight simulators in accident investigations should be approached judicially [4].

The training qualities and effectiveness from flight simulators are dependent on a number of factors, which include the quality of the simulator, the instructor's skills and the teaching curriculum. Flight simulators provide invaluable training in preparing pilots to cope with extreme conditions but awareness should be applied in recognising the basic limitations of flight simulators such as the effect of restricted motion cues and how such limitations might impact individual exercises. The time constraint in completing the curriculum also hampers the opportunity to explore situations that are outside of the syllabus. Instead of asking, "What is the envelope of the flight simulator?” the question should be rephrased to "What is my specific training objective and can the flight simulator support it?” Often a simple approach in flight simulators yields good results if not better.

[9] conducted an experiment and their results show that in most cases, a 3-DOF simulator is capable of producing motion simulation quality comparable to that produced by a 6-DOF simulator. Implementing a complex model may seem beneficial but shortcoming such as the lack of repeatability may prevail over the benefits of a sophisticated model since the degree of the effect is dependent upon the profile flown by the pilot. However, simple models may not allow more sophisticated simulation training or exploration of other more dangerous manoeuvres. It may also not expose some fundamental flaws of aircraft manufacturing or current procedures.

Modelling must be the best achievable if the aircraft systems and procedures were to be questioned with any confidence. In addition, low quality flight simulators may produce negative transfer of training. Most flight simulator users are unaware of the implementation and modelling techniques, and are therefore uninformed of the limitations and short falls. These issues require flight simulator users to be educated by the industry [10].

Pilots have reported that flight simulators are typically harder to fly than the real aircraft that they represent. Some of the difficulties in simulated flying are the limited field of view, scene distortion, absence of depth perception, attenuation or absence of motion cues, and response delays that are inconsistent with visual, motion and instruments [11]. For example, a curve vision is better for flight simulation as in a screen that wraps around the simulator cockpit since it will provide the pilot the same type of view available during flight [12]. Modelling requirements also affect flight simulation and have been dictated by computing equipment limitations. Some of these issues and concerns are discussed by [13].

Technology has always been driving the development of FFS. Despite having discussed some of the flight simulators' shortfalls and limitations, FFS have become very sophisticated and significant achievements have resulted in the highest approved category of simulators that allows zero flight time for training pilots converting to a new aircraft type – the level D FFS. With the high level of maturity in FFS, training requirements should be driving further development of training and simulation. From a training point of view, raises the following question "What is effective and efficient training?" An attempt to answering this question would entail establishing the training needs, what should be trained and how should training be carried out? According to [5] "effective training" is to ensure that all training objectives are met and " efficient training" is training in the shortest possible time at the lowest cost while meeting all training objectives with the least change of failure.

### 2.3 Skills Transfer

The use of a virtual environment has potential for training of complex and real-world tasks. However, there will be considerable danger if ineffective research methodologies are being used in flight simulation research and this will result in failure to resolve crucial issues for the same reasons. Designing virtual training is more that just an engineering problem, it is also on effective transfer of training of virtual environments or any other form of real-time simulations. Students who performed well in a flight simulator do not necessary perform well in real life situation. Studies have been conducted that indicate good transfer of training being associated with poor transfer performance. There is no evidence to support that the much desired properties of high fidelity and sense of psychological immersion do anything to enhance training effectiveness of simulations or virtual environments [2, 14-16].

Skill transfer occurs when an individual is able to perform a task easier as a result of having previously practised a different task. Identification of the elements that support transfer and development of instructional strategies that selectively enhance a trainee's skill with those elements could contribute substantially to the design principles of training devices. [17] conducted a study on the transfer of skill from a computer trainer to actual flight and found that those trained with computer game as part of their training performed better and have higher final percentage of graduation than those who did not. Hence, computer based training has proven to be valid but there remain questions as to what skills are exactly being transferred and how. The success in using a flight simulator for training purposes has led the Israeli air force personnel to incorporate the computer game into their regular training program.

[18] conducted a quasi transfer experiment using augmented visual feedback that used 8 pairs of "F-poles" to define the boundary of the desired path to the runway aim point and automatic

adaptive flight path predictor symbol as guidance to indicate the azimuth and elevation directions. A quasi transfer experiment is one that is trained with different simulator configurations then followed by testing on a criterion simulator configuration. Their experiments show that quasi transfer landing experiment yielded good results if moderately detailed pictorial airport scene were used in early training and the overall quasi transfer experiments demonstrated a relationship between training in a research simulator and the performance in an airplane. Their results show that students who received landing practice in a simulator performed better than those without. This represented a potential savings of 1.5 pre solo flight hours per student, which translates to an effectiveness ratio of 0.75.

Contrary to intuition, in an experimental study carried out by [19], a transfer of training to crosswind conditions was found to be better following training without crosswind than following training with crosswind. This type of results shows that there is a need for theoretical conception of skill transfer that does not rely on the notion of fidelity. [20] pointed out the importance of how pilot training should be carried out and how accident prevention is being approached from the wrong approach - that is by regulating what pilots should or should not do rather than training them to deal with the situation effectively.

A common response from commercial airline pilots to the question, “How would you land an aircraft should you suffer an engine failure during flight?” is to land straight ahead from the aircraft’s current heading position. This well ingrained procedure is a very common technique taught by flight instructors, which F.A.A. has recommended for such situation. However, not all geographical scenarios allow a straight ahead landing such as a well-developed urban area that lies ahead of the engine failure point. How different would the training have been if there were suitable landing fields on the right or left or even aft of the airplane engine failure point? It is important that student pilots are trained effectively because certain piloting habits are hard to change once they are developed in the early stages of the student pilot training.

[21] carried out a series of tests on training methods and their results show that subjects preferred flight simulator training over lecture styled format. Although flight simulators are capable of replicating scenarios but there are no guidelines or curricula that can increase the awareness of aeromedical issues. Their experimental results show that their simulator-based curriculum was assessed to be 250% - 350% higher than the existing conventional training. Some of the improvements identified in their experiment include improvement in cognitive domain from comprehension to evaluation, improvement in psychomotor domain from set to origination and improvement in affective domain from responding to characterization.

[22] discussed some issues on the evaluation of training devices such as flight simulators for aircrew training. This is an important issue since millions are spent on flight simulators and evaluations are not tested against criteria that prevail in systems engineering. He presented arguments that both the transfer of training experiment, where competence in the aircraft is required as evidence of a simulator’s training value and the rating methods [23, 24] of evaluating the worth of a simulator are flawed.

### 2.4 Delay in Modelling

Despite the advancement of technology, a flight simulator cannot perfectly replicate a flying environment. The simulation fidelity of flight simulators is dependent on the accuracy of the aircraft model and the update rate of the model dynamics. At present, the flight simulation industry is still trying to overcome and to understand the effect that delay has on the transfer of training. Transport delay is the time between the input to and output from a flight simulator that is not due to the aircraft dynamics. This inherent problem, which destabilizes the system in flight simulation, is inevitable since a finite amount of time is required by the hardware and software to recreate the virtual environment. Typically, hardware transport delay is the largest contributor to the overall transport delay.

The effects of delay on flight simulators can be generalized to either control degradation or simulator sickness. Experiments on simulating demanding tasks have shown that time delays can significantly degrade the flying qualities. Time delays, which are often associated with the control systems time delay, has profound effects on the longitudinal and the lateral flying qualities for precision fighter tasks since the allowable time delay and the rate of flying qualities degradation with time delay are function of the level of task precision, the pilot's technique and the subsequent pilot's response [25]. "High stress" realistic tasks will expose some of the flying qualities problems related to time delay, therefore, flying qualities evaluation criteria should include time delay [26]. As mentioned by [27] delays have a greater effect on simulating high-performance fighter aircraft than for simulating heavy transport aircraft that is used for less demanding task.

[28] carried out an experiment and an analytical pilot modelling study to investigate the effect time delay has in manual control systems. He studied the effects time delay have on the human-operator controlled-element transfer function and its performance scores. His results show that for a variety of controlled elements, time delay can cause significant regression in pilot-vehicle crossover frequencies and significant pilot lead generation. He concluded that there is a definite link between system time delay and pilot workload since pilot lead generation has been shown to contribute to pilot workload directly. [29] conducted a research on how time delay manifests themselves into the flight simulator in both the time domain and frequency domain. They also investigated the effect various integration methods have on delay and suggested various compensation techniques that can help to reduce time delays. [30] conducted an experiment on the effect delays have on performance, control behaviour and transfer of training in simulated aircrafts with different dynamics responses using subjects with no experience with flight control tasks. Their results show that delay has a greater effect on the transfer of training for the simulated aircraft with sluggish dynamics and it also contributed to pilot-induced oscillations.

[31] carried out an experiment on transport delay and the effects they have on the training effectiveness of simulation. He found that transport delay has essentially stayed constant even with the increase in sophistication in simulators, which correspond to an increase in computational complexity since they are being compensated by the increase in computing speed. However, the effects delays have on training effectiveness are not constant due to the complexity on how the many computers are networked together. The average delay in his experiment was 148 ms and comments from pilots were that it did not fly like the real thing although all tasks could be accomplished without much difficulty.

[32]'s experiment show that the flying performance is tolerable up to a maximum delay of 141 ms while [33]'s simulation experiment reported that their subjects cannot clearly distinguish delays between 90 ms and 200 ms but the effects of a high delay of 300 ms can always be experienced along with an associated increase in workload. [34] conducted a study on the effects time delay have on manual flight control and flying qualities during in-flight. Their findings show that as the time delay increases, the aircraft has the tendency to overshoot and oscillations became evident leading to pilot induced oscillations. A time delay of up to 150 msec was found to be tolerable in their simulation experiment. Transport delay is also known

to affect landing manoeuvres and formation flying tasks [35]. In a sidestep landing manoeuvre experiment carried out by [36], a delay of up to 200 ms was found to be acceptable but a delay of 300 ms caused difficulty for pilots to align their aircraft to the runway.

Visual and motion system delays are deleterious and detrimental to both an individual's control performance and well-being but visual delay is far more disruptive to a simulator operator's control performance and physical comfort than is motion delay [37-41]. An extensive list of references on the effects of delay was reviewed by [42] and delays ranging from 100 ms to 200 ms from CGIs have been known to be have an effect on the control behaviour of pilots on flight simulators.
Data transmission over long distances introduces data latency that can introduce artefacts in the simulation. In a networked simulation, delay in an aircraft's simulated flight path can cause the attacking pilot to change his/her tactics in order to better position himself/herself, hence, affecting his flying strategy in a real life situation. Analysis of delays from networked flight simulators carried out by [43] revealed that intra-simulator delay is a significant problem for flight task simulations such as air-to-air-combat, formation flight, air-to-air-refuelling, and target hand-off. A delay of 250 ms was found to be acceptable with little degradation in a networked simulation of two-ship air-to-air combat simulation, [44]. A conservative estimated delay of up to 300 ms was found to be tolerable by the defender in an investigation on the effect delay has on dome-to-dome simulation link for different air combat manoeuvring with emphasis on scoring, guns and missile, [45].

Time delay affects the transfer of training from a simulator and some compensation methods for reducing time delay in flight simulations have been suggested by [37, 41, 46-50]. In summary, many experiments have shown that a time delay of up to 200 ms is tolerable but the FAA's recommendation is to keep it below 150 ms [11, 34, 48, 51-53]. The military specifications for piloted vehicle flying qualities (MIL-F-8785C) are 100 msec, 200 msec and 250 msec for Level 1, 2 and 3 respectively [34].

## 3 OPTIMISATION OF FLIGHT TRAJECTORIES

The study of safe landing of aircraft is a very important issue in the aviation field and is considered by pilots as the most demanding task in every flight. Many accidents have occurred during the landing phase of flights, some of which were beyond the pilot's control, some were due to human error, while some could have been successful if only a more optimal landing manoeuvre was carried out. Unfortunately, it is the disastrous failed landings that became a statistics with the National Transportation Safety Board (NTSB) and those who landed safely or with minor damage generally are not reported to Federal Aviation Authority (FAA) or NTSB. Hence, the statistics gathered are skewed or biased towards failed attempts.

The research problem in this study considered the search for the best landing trajectory for a forced landing manoeuvre of an aircraft after an engine failure. Such situation could occur after take-off [54] or during a level flight at any altitude above ground level (AGL) [55]. When an engine failure occurs in an aircraft and no additional power is available, the pilot must select a suitable location to land safely with the limited amount of energy available from the engine failure position. The general recommendation is to land straight ahead and Rogers' studies [54] confirmed the high rates of using this ingrained technique. However, he suggests that, for forced landings from a higher altitude, a turnback manoeuvre may be flown because higher altitude allows for more time in the air. This research is also an extension of Rogers' forced landing manoeuvre where the search for optimal landing paths begins after the pilot has selected a practical landing location on the ground that is within range after an engine failure. A study on the effects vertical atmospheric disturbances have on a forced landing manoeuvre was also carried out.

### 3.1 Problem Description

Landing an aircraft that has suffered an engine failure during take-off is one of the classifications of a forced landing and is the focus of this study. The general recommendation in the aviation literature for such a situation is to land straight ahead [56, 57]. For example, FAA regulations recommend that pilots land straight ahead and should never attempt track reversals in an effort to land on the departure runway. The present research problem is an extension of a forced landing manoeuvre on the Beech E33A Bonanza single engine aircraft considered by [58] based on [54]. The problem considered in this forced landing assumed an engine failure at 650 ft AGL after take-off. It used the engine failure point as the reference point for all distances calculated. It was assumed that the transition in speed occurred instantaneously and the effects of landing gear retraction/extension were not considered.

A graphical interpretation of the forced landing after an engine failure at an arbitrary altitude is shown in Figure 2. This research took the approach of an ensemble of probability of landing within a specified tolerance from a pre-selected location and not as an optimal control problem of the deviation from the flight trajectory during a forced landing manoeuvre. In other words, what are the chances of the pilot performing the landing task with maximum probability of landing on a pre-selected landing site? The calculations performed in this study used the general flight dynamics equations [59] and data based on the Beech Bonanza E33A retractable aircraft characteristics obtained from Rogers as shown in Table 1. The data for initial takeoff ground roll and distance to clear 50 ft obstacle are obtained from Rising Up Aviation Resources[2].

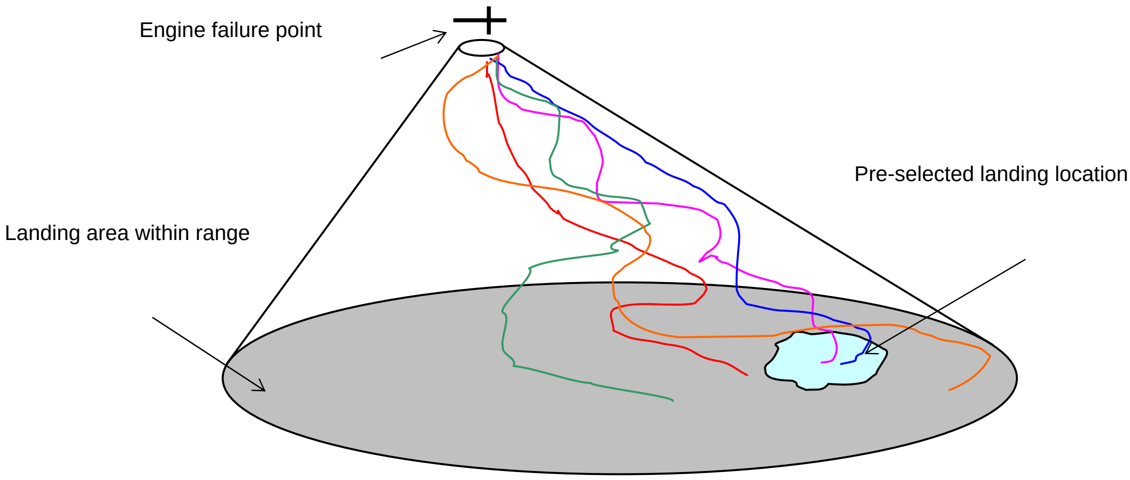



Figure 2: Forced Landing Area

*Table 1 Beech bonanza Model 33A Characteristics* [54]

[2] Data available online at http://www.risingup.com/planespecs/info/airplane117.shtml. 2003.

| Parameter | Value |
|---|---|
| Gross Weight, lb | 3300 |
| Wing Area, $ft^2$ | 181 |
| $L/D_{max}$ | 10.56 |
| Power, brake horsepower | 285 |
| Propeller | Constant speed 3-blade |
| $V_{max}$, mph | 208 |
| $V_{cruise}$ at 65%, mph | 190 |
| $V_{stall(clean)}$[a] power off, mph | 72 |
| $V_{stall(dirty)}$ power off, mph | 61 |
| $V_{L/Dmax}$[b], mph | 122 |
| $V_{\gamma max}$[c] at sea level, mph | 91 |
| $V_{R/Cmax}$[d] at sea level, mph | 112.5 |
| R/C at sea level and 3300 lb, ft/min | 1200 |
| Parabolic drag polar | $C_D = 0.019 + 0.0917C_L^2$ |
| Takeoff: Ground roll, ft | 880 |
| Takeoff: Over 50 ft obstacle, ft | 1225 |
| Landing: Ground roll, ft | 625 |
| Landing: Over 50 ft obstacle, ft | 1150 |

[a] Gear and flaps retracted.
[b] $L/D_{max}$ = maximum lift to drag ratio.
[c] $\gamma$ = glide angle.
[d] $R/C_{max}$ = maximum rate of climb.

### 3.2 Atmospheric Model

The simulation of atmospheric turbulence is of considerable importance and is a critical component in any aircraft simulation and in trajectory optimisation development. Atmospheric disturbances are very random by nature and so are its magnitudes and the frequencies of occurrence. They are affected, for example, by the geographical location, the weather and the time of the year. For this study, the thermal distribution models with velocities varying from –9.84 ft/sec to +9.84 ft/sec in discrete step size of 3.28 ft/sec are assumed to "jump" from one state to another. For convenience, the thermal jumps are assumed to occur at every 350 ft drop in altitude, regardless of the horizontal distance travelled since calculations were carried out for every 50 ft drop in altitude. The approximation step size of 350 ft drop in altitude was used because while using an estimated average sink rate of 20 ft/sec, the thermals change state every 16.25 secs, which is very close to the estimated phugoid period of 15 sec. Therefore, 49 different thermal distributions, with one "jump", were used to simulate the forced landing manoeuvre with thermal distribution for an engine failure altitude at 650 ft AGL as shown in Figure 3. Note that discritising the thermal distributions in terms of altitude drop resulted in thermals with various horizontal sizes. This is because the up and down drafts affect the aircraft's net sink rate during the descend manoeuvre, which in turn affects the horizontal distance travelled.

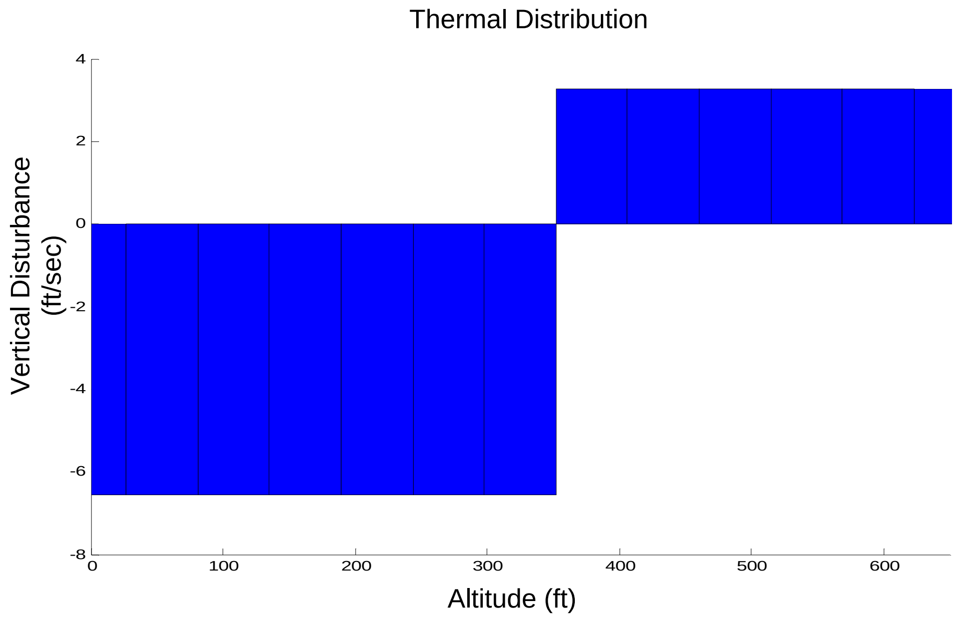



Figure 3: Vertical Thermal Distribution

# 4 GENETIC ALGORITHMS

In this research a trajectory optimisation was being undertaken using Genetic Algorithm to search for optimal landing manoeuvres for a forced landing of an airplane after engine failure using a simplified analytical model for the Beech Bonanza model E33A retractable-undercarriage aircraft.

## 4.1 Genetic Algorithms Theory

Drawing parallels from natural selection, [60] proposed the theory of GA in the early 1970's which imitates the evolutionary processes in nature. Evolution can be considered as a form of an optimisation problem where only the fittest individuals will survive and reproduce, also known as the "survival of the fittest". GAs use crossovers – a probabilistic mechanism for randomising chromosomes, and mutations – a perturbation mechanism, as search mechanisms to generate a sequence of populations. The most rudimentary unit, the genes, which can take the form of different alleles, are combined to form chromosomes that control the "keys" to the survival of the individual in a competitive environment. Evolution occurs when the chromosomes from two parents are combined during reproduction and a new gene pool is formed from combinations generated through either crossover or mutation.

GAs perform parallel, non-comprehensive search in the hope of finding the global maximum, if not a very near optimal solution, to optimisation problems. The procedure to solve a complex problem using GAs is to define the search space and to custom design a coding scheme for the solutions in the search space tailored to the problem. This process is known as genetic representation[61]. A fitness function is then designed to evaluate the potential solutions, and the "better" ones are kept for subsequent regenerations and the "inferior" solutions are discarded. The next generation of solutions are created by applying the crossovers and mutations genetic operators to evolve solutions for further fitness evaluations. The optimisation process terminates when either an acceptable tolerance in results is obtained, or when it has processed a specific number of generations, or when no improvement in fitness value is encountered after a number of consecutive generations. The GA cycle is shown in Figure 4. The three most important features are fitness function, the genetic encoding and the genetic operators.

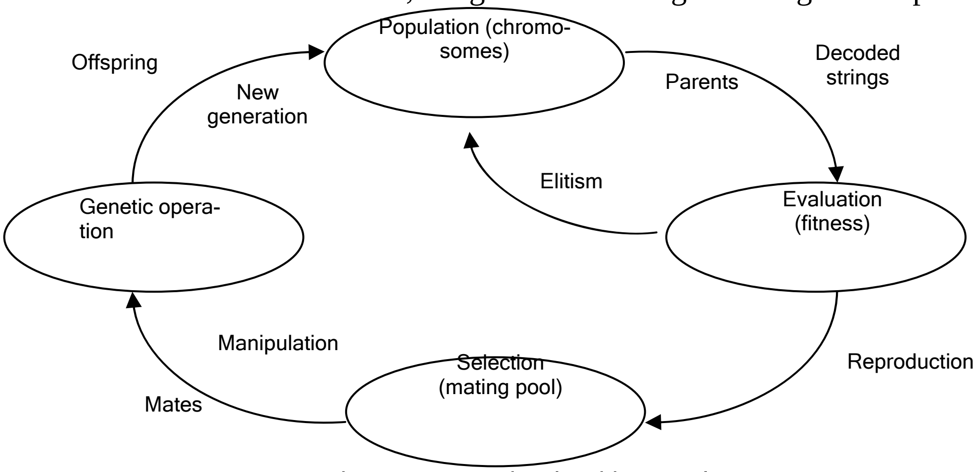



Figure 4: Genetic Algorithm Cycle

GA is a relatively new optimisation method compared to the traditional gradient search method, which has difficulties for discontinuous or non-smooth functions. In solving optimisation problems, GAs have the advantage that no derivatives have to be found but they have only to utilize the governing equations in the problem considered. The trade off in not using gradient information is that it does not guarantee a minimum point but will locate results that are very close to the optimal solution. Other optimisation methods such as gradient method may be able to locate better optimal solutions but may suffer computational time. GA is not an alternative nor is it a replacement method to other traditional optimisation methods but it is a valid complementary optimisation technique. In simulation, obtaining acceptable results rapidly is more valuable than spending an enormous time searching for the optimal point and GA is capable of doing so.

### 4.2 Real-Value GA Operators

A real-value representation was used since it helped to exploit the numerical properties of a candidate solution by exploiting the solution gradients and information from the function's landscape. The GA real-value chromosomes are represented by a vector $\vec{x} = (x_{1, \ldots} x_n)$, where n is the chromosome length. The chromosome length is equivalent to the number of variables used to represent the domain. Each gene, ($x_k$), in the chromosome is bounded by an upper limit ($x_{max}$) and a lower limit ($x_{min}$) specific to the gene.

A brief description from [62] is presented here for the different operators used for a real value encoding. The genetic operators used for real value encoding in this analysis consist of three types of mutation operators and three types of crossover operators:

***Uniform mutation*** randomly mutates a gene in the chromosome with uniform probability distribution to any value within the real-valued domain range. This operator is important in the early phases of the evolution process, as the solutions are free to move within the search space.

***Boundary mutation*** mutates a gene to either the lower boundary value or the upper boundary value for the real-valued range. This operator is very useful for GAs with constraints.

***Non-uniform mutation*** mutates a gene by a factor that is a function of the difference in value between that particular gene and either of its boundary value, and the generation number. This mutation probability will decrease to 0 as the generation number increases. This type of mutation is used for local fine-tuning of genes where the operator will initially search the space uniformly and very locally at later generations.

***Arithmetic crossover*** linearly combines the genes from two parents to produce two children.

***Simple crossover*** randomly selects a point in a chromosome as a crossover point which is very similar to the traditional one-point crossover.

***Heuristic crossover*** uses the values of the objective function to determine the direction of the search and it may or may not produce an offspring. It is responsible for local fine-tuning and search in the promising direction.

All of the six genetic operators described were required to explore the search space adequately and were used equally to prevent premature convergent without regard to fitness. For example, arithmetical crossover would tend to drive the population to the numerical center of the search space very quickly, regardless if it yields good fitness values, and boundary mutation would set the gene to either of its boundary value. However, the use of other operators will prevent such problem. It is through the combination of these powerful crossover and mutation operators developed by Michalewicz that the search space can be explored and good genetic material exploited. In order to randomise the use of the three types of crossovers and mutations uniformly, the populations were randomly chosen for the different types of crossovers and mutations. The three types of crossovers and mutations were applied equally to all the randomised populations in every generation to allow equal distribution of genetic operators.
The GA in this analysis used tournament selection, whereby two chromosomes were selected from the population and compared at any one time to select the fitter chromosome for crossover and mutation. This selection method prevented fitness scaling where a few highly fit chromosomes may dominate the parent population. It also used elitism where a certain number of the best chromosomes from the previous generation are cloned to the present generation.

## 5 RESULTS

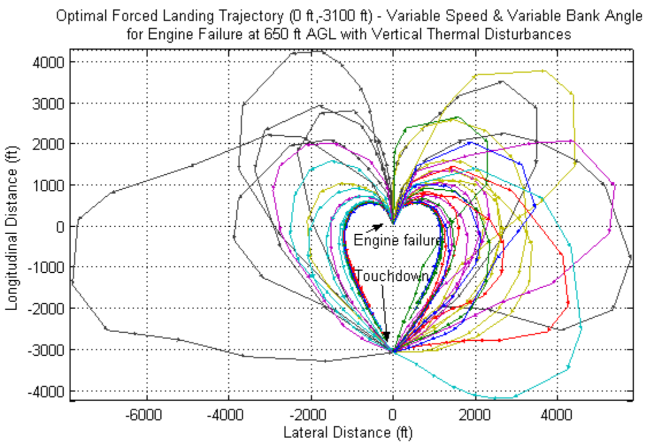
The results for the GA with variable speed and variable bank angle, and with thermal disturbances for touchdown distance from the three pre-selected landing locations are shown in Table 2. The best landing flight path from each of the 49 thermal profiles and their average flying parameters as shown in Figures 5 – 7 show general flight paths that resemble the flight paths found for the GA in still air condition. For all the three pre-selected landing locations, the flight paths with thermal disturbances trace flight path envelope that are much broader than in still air condition.

Table 2 Results for GA with Variable Speed, Variable Bank Angle and Thermal Disturbances

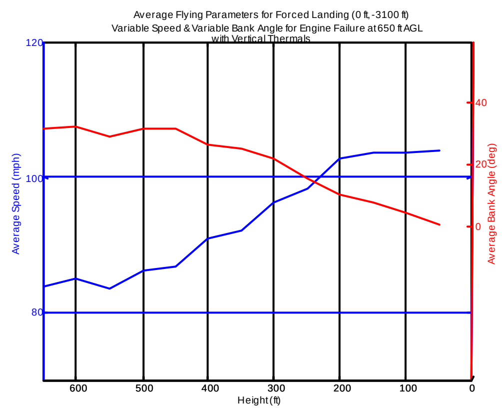
| Pre-selected Location | Global Minimum Distance | Average of the Minimum Distance from each Turbulence Profile | Average Minimum Distance from 4900 trials | Probability of Landing ≤ 1 ft from pre-selected location |
|---|---|---|---|---|
| (0 ft, -3100 ft) | 0.0018 ft | 261.4436 ft | 294.9192 ft | 32 % |
| (3000 ft, 3000 ft) | 0.0004 ft | 0.0062 ft | 0.1025 ft | 49 % |
| (500 ft, 200 ft) | 0.0011 ft | 27.3698 ft | 42. 4508 ft | 40 % |

The results show that the GA with variable speed and variable bank angle, and with thermal disturbances have successfully found suitable combinations of the aircraft speed and bank angle to land near the pre-selected locations. However, the average distance from the pre-selected location for the location (0, ft, -3100 ft) is far compare to the results for the other two locations but the probability of landing within 1 ft from the pre-selected for all the three locations remain consistent. The overall distance from the pre-selected location for with thermal disturbances is farther than the distance for still air condition. This indicates that vertical disturbances have significant effect on the forced landing manoeuvre.

Figure 5-a shows the best forced landing flight paths with thermal disturbances for each of the 49 thermal profiles for the pre-selected location (0 ft, -3100 ft). Two general forced landing paths exist since the pre-selected location is located along the airplane's line of symmetry at engine failure point. The aircraft average flying speed and bank angle at each 50 ft decrement in altitude, and the airplane's final heading statistics to land at the pre-selected location are shown in Figure 5-b. The flight path envelope for this case is a very wide flight path envelope and a wider range in the airplane's final heading compare to the still air condition. The major difference in the average flying parameters with thermal disturbances for this location is a higher airplane's turn speed of approximately 84 mph and a lower bank angle of approximately 30° compare to the still air condition of approximately 76 mph and a bank angle of 40° respectively. These results show that a wider range in vertical disturbance has a significant effect on the forced landing flight paths.




| # runs | Final Heading |
|---|---|
| 41 % | $64° \le \psi \le 154°$ |
| 59 % | $198° \le \psi \le 291°$ |

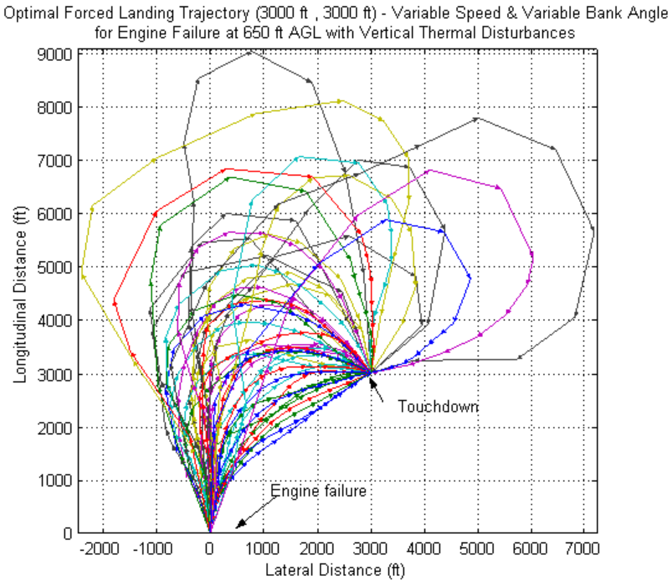



(a) (b)

Figure 5: Optimal Forced Landing (0 ft, -3100 ft) Variable Speed and Variable Bank Angle at 650 ft AGL with Vertical Thermals

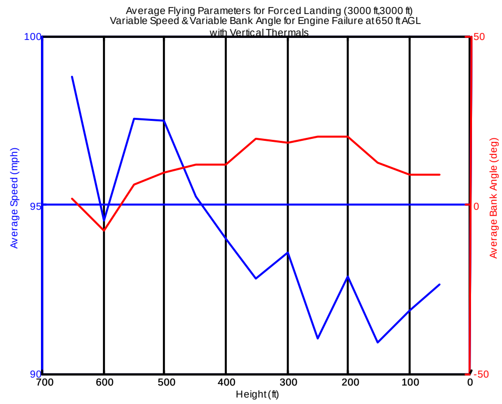
Figure 6-a shows the best forced landing flight paths for each of the 49 thermal disturbances for the pre-selected location (3000 ft, 3000 ft). The aircraft average flying speed and bank angle at each 50 ft decrement in altitude, and the airplane's final heading statistics to land at the pre-selected location are shown in Figure 6-b. The flight path envelope for this case is very much wider than the flight path envelope in still air condition. The major difference in the average flying parameters with thermal disturbances for this location is a higher initial airplane's turn speed of approximately 99 mph and an approximate zero bank angle for the 1st 50 ft drop in altitude. This is followed by a slight left bank at a reduced airplane's speed for the next 50 ft drop in altitude and a continual decrease in the airplane's speed to approxi-

mately 93 mph an a bank angle of approximately 10°. Most of the airplane's final heading is still within 090° and 135° but there is a decrease in final heading between 135° and 180° while an increase in final heading between 180° and 270°. This is due stronger updrafts in the thermal disturbances where the sink rate is reduced and the airplane is required to fly a longer path, hence, arriving at greater than the 180° approach. The stronger downdrafts in the thermals with result in a higher sink rate, hence, a more direct or shorter flight path is necessary.




(a)

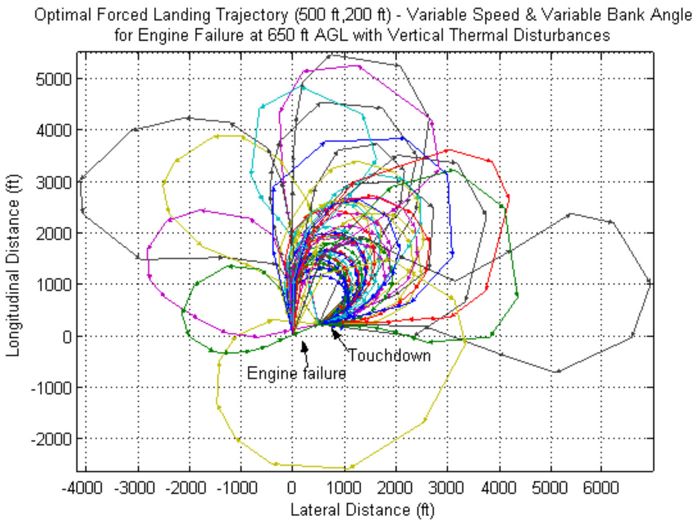
| # runs | Final Heading |
|---|---|
| 0 % | $000° \leq \psi < 045°$ |
| 16 % | $045° \leq \psi < 090°$ |
| 34 % | $090° \leq \psi < 135°$ |
| 25 % | $135° \leq \psi < 180°$ |
| 25 % | $180° \leq \psi < 270°$ |




(b)

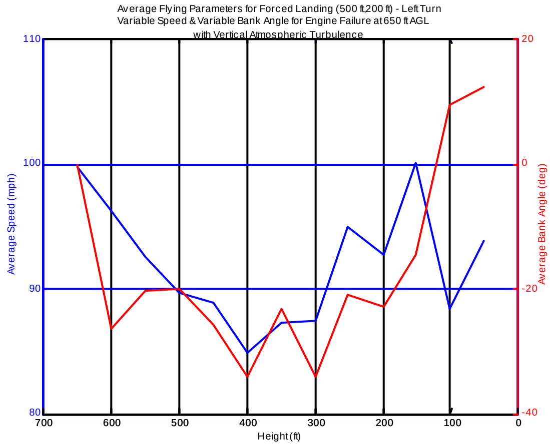
Figure 6: Optimal Forced Landing (3000 ft, 3000 ft) Variable Speed and Variable Bank Angle at 650 ft AGL with Vertical Thermals

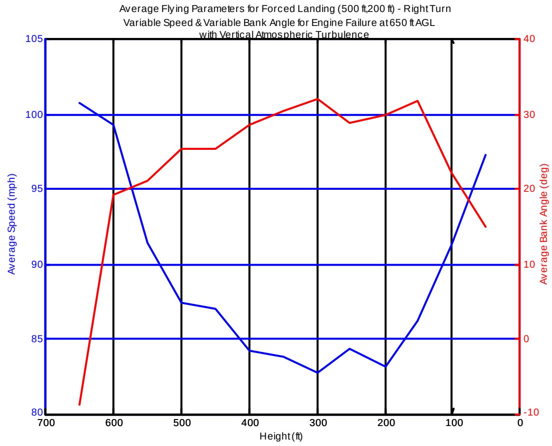
Figure 7-a shows the best forced landing flight paths for each of the 49 thermal disturbances and the airplane's final heading statistics for the pre-selected location (500 ft, 200 ft). The aircraft average flying speed and bank angle at each 50 ft decrement in altitude to land at the pre-selected location are shown in Figures 7-b,c. The average flying parameters for this location begins with a higher initial airplane's speed, a higher turn speed, and a lower bank angle during turn compare to still air condition. There is also a reduced number of flight paths that turn toward the pre-selected location and an increased number of flight paths that turn away from the pre-selected location compare to still air conditions. The wider flight paths envelope traced by this case is due to stronger up and down drafts in the thermals, causing the airplane to fly a longer path while the downdrafts in the thermals cause the airplane to fly a smaller radius.




| # runs | Final Heading |
|---|---|
| 12 % | 66° ≤ ψ ≤ 168° |
| 88 % | 179° ≤ ψ ≤ 293° |

(a)




(c) (b)

Figure 7: Optimal Forced Landing (500 ft, 200 ft) Variable Speed and Variable Bank Angle at 650 ft AGL with Vertical Thermals

## 6 CONCLUSIONS

The GA results for a forced landing of an aircraft after an engine failure with vertical thermal disturbances for each of the three test locations were considered. The results obtained trace an envelope for the most probable landing paths for each of the pre-selected landing location considered, touching down very close to the intended touchdown point on the ground. The vertical disturbances have the effect of widening the flight path envelope for each of the three locations considered. This is as expected since vertical turbulence velocity components effectively changes the vertical descent rate, forcing a change in the forced landing manoeuvre to land at the pre-selected landing locations. The vertical disturbances have the most effect on the straight glide manoeuvres and are less sensitive to the turn manoeuvres. This effect is very well depicted in the forced landing analyses with vertical thermal disturbances where longer and wider the flight paths are obtained. The results from various GA search have confirmed GA's effectiveness to explore the solution domain as well as its capability to successfully identify the most promising trajectory paths to a forced landing manoeuvre.

GA is a relatively new optimisation method compared to the traditional gradient search method, which has difficulties for discontinuous or non-smooth functions. In solving optimisation problems, GAs have the advantage that no derivatives have to be found but they have only to utilise the governing equations in the problem considered. The trade off in not using gradient information is that it does not guarantee a minimum point but it will locate results that are very close to the optimal solution. Other optimisation methods such as gradient method may be able to locate better optimal solutions but may suffer computational time. GA is not an alternative nor is it a replacement method to other traditional optimisation methods but it is a valid complementary optimisation technique. In simulation, obtaining acceptable results rapidly is more valuable than spending an enormous time searching for the optimal point. In this study, the objective is to be able to obtain a solution quickly in a short time, namely a fast algorithm that can be used on board a small aircraft and can calculate the optimum trajectory quickly in the case of a forced landing.

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