Flight Control System Design Optimisation via Genetic Programming

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Abstract

More than 60 percent of fatal aircraft accidents are reported as being caused by human error. In addition, the current method of the design of autonomous control is very costly but not totally reliable; therefore, the new method to develop control laws should be approached in a new automated way. This paper presents design, optimisation and validation of control system for a fighter aircraft via a combination of Genetic Algorithm (GA) and Genetic Programming (GP). An altitude hold autopilot is constructed to cope with the disturbances in order to reduce pilot workload in altitude hold mode. Furthermore, the possibility of guiding the aircraft to a desired position and performing a banked turn has been investigated. Even though the developed control structure is substantially constrained, the result demonstrates that the control law is effective, reliable and robust as the aircraft can withstand severe vertical wind gust and error from inaccurate Global Positioning System (GPS) equipment in altitude hold mode. Also, the altitude response while the aircraft is guided to a designated point and is performing a banked turn is minimized. Thus, pilot work load could be potentially reduced and accidents caused by human factors could be minimized with the development of new methodology.

1. Introduction

Nonlinear aircraft simulations are advantageous for control law design and validation, optimisation, dynamic analysis, pilot training, and etc. Designing flight control system often incorporates nonlinearity, uncertainty and requires a priori knowledge to define the structure of the control law. Sometimes, the complexity of the system is so substantial that an insightful analysis cannot be achieved.

There has been an increasing interest in intelligent control technique such as neural networks, fuzzy logic, adaptive control and evolutionary and genetic algorithms, which aim to address complex, nonlinear and stochastic problems [13]. However, most of the techniques aim to search for optimal values of coefficients for a control law or structure which has been defined prior to the search process. The combination of Genetic Algorithm (GA) and Genetic Programming (GP) can automatically solve problems without the knowledge of form or structure of the solutions. Furthermore, the techniques are conceptually simple and robust to dynamic changes as it can be adapted to changing environment without a complete restart.

A number of improvements regarding safety concern in the area of pilot workload can be observed as new flight displays and cockpit devices are equipped to enhance pilot performance. Nevertheless, more than 60 percent of fatal aircraft accidents are reported as being caused by human error [14]. Moreover, the control design of current Unmanned Aerial Vehicles (UAVs) is very costly but not totally reliable because statistics show that the loss rate per 100K flight hours of high-end UAVs such as Predator and low-end UAVs such as Pioneer and Hunter can be as high

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as 60 and 170, respectively. There are also other factors such as instrumental error, strong wind disturbance and uncertainties including icing condition and stuck aerodynamic surfaces. It is these unpredictable phenomena that urge the needs for automatic optimisation algorithm to enhance air safety.

Although the capability of the algorithm is enormous, the architecture of the system is limited to only proportional, integral and derivative (PID) structure because it is simple, verifiable and most applicable from control system engineer point of view. A six degree of freedom nonlinear F-16 MATLAB/Similink model will be utilized in developing a control law by a combination of genetic algorithm and genetic programming techniques.

2. Literature review

The objective of optimisation technique is either to search for minimum or maximum value of a function which is often referred as a cost or fitness function, respectively. A suitable optimisation algorithm should ensure that the sought value is the global optimum, which is a combination of parameters having the highest/lowest fitness in the search space, not the local optimum that has higher/lower fitness compared to its surrounding but not the real highest/lowest values of the function [6]. Evaluating all points in the search space will certainly arrive at the best solution but it is often become less practical as the dimension of the search space increases.

Genetic algorithms (GAs) imitate natural evolution which is a process that animals and plants evolve in accordance with environments to obtain an optimum form [6]. Each offspring is not a perfect copy of its parents. If its features are favourable, it will have more likelihood to survive to the next generation. Complex and nonlinear problems can be automatically solve with the combination of GA and GP because the algorithm does not require deep priory knowledge and predefined structure of the controllers to be optimised. They can be used to design multivariable offline and online tuning of PID controller, and can also be used to optimise fuzzy neural networks [2,7]. Application to flight control system is not limited only to low-speed flight but also include hypersonic region [4].

There are a number of advantages of genetic algorithms including conceptual simplicity, robust to dynamic changes and less required expertise to solve a problem. The algorithm consists of initialization, iteration and selection in accordance with its performance index. Through the process of iterations and selections, the global optimal solutions can be found [12]. Furthermore, evolutionary algorithms can be adapted to changing environment unlike the traditional approaches that require a complete restart. In addition, Sivanandam and Deepa [12] contend that it is less adequate for the technique to obtain human guidance because this behaviour can disrupt the program's routines and lead to error.

Clearly, the algorithm to design the control law should incorporate pilot feedback and can be adapted to new configuration with ease; therefore, genetic algorithms should be the best candidate because the algorithms use only the function values in the search process to obtain a solution regardless to how the functions are evaluated. Hence, this technique can be applied with to various kinds of problems including nonlinearity [3].

3. Control

Control theory has been developing since 1930s. PID controller with schedule gains may be the most desirable in traditional feedback control design because it can eliminate disadvantages of all three controllers [9]. However, gain scheduling cannot perform well in environment where parameters change rapidly over a small time interval [15]. It is possible to solve this problem but the process can be costly and time consuming [15]. Although control laws such as H_∞ robust control and fuzzy neutral control have been developed to overcome gain scheduling capability and address system nonlinearity, model uncertainties and a wider flight envelop [15], for example, it is found that most of controllers incorporated by industry are based on PID structure. PID controllers are simple and can offer effective solution to both transient and steady state problems [7]. Hence, the control law structure is developed and optimised in PID form.

4. Genetic Algorithm and Genetic Programming

The procedure of genetic algorithm and genetic programming is identical (see Figure 1) but some operations in each stage are quite different so they will be described separately.

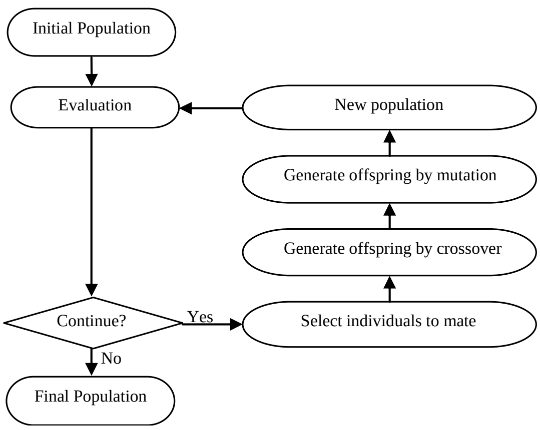

Figure 1 Genetic Algorithm and Programming diagram (modified from [6,11])

Generally speaking, both techniques have a strong resemblance but there are primary four differences [4]:

- Solutions generated by GP are usually coded as tree structured, having variable length when GA typically uses fixed length and structure chromosome.
- GP normally incorporates syntax that governs meaningful arrangement of information on the chromosome while GA does not.
- During reproduction process, GP has operators that can maintain the syntax of the tree-structured chromosomes.
- Almost all GP solutions are coded in the way that can be directly executed by decoder; however, this is a rare practice in GA.

4.1 Genetic Algorithm

The GA begins by randomly generate the initial population which is encoded to facilitate the search process. A string of digits called a chromosome is used as a representation of possible solutions. McGookin [8] suggests an encoding method by using a string of five genes instead of binary bits. These genes are decimal integer ranging from 0 to 9. Figure 2 demonstrates the mechanism of this method. The possible solutions from this encoding can range from 0 to 99.99.

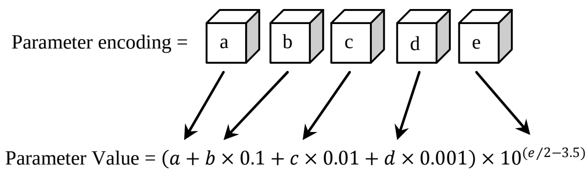

Figure 2 Parameter encoding mechanism [1]

The randomly generated integers are then decoded and fed into a function to evaluate their fitness which will be used to determine whether process will be terminated or the generated integers or “individuals” will undergo selection process. In selection process, fitness is used as a basis to select individuals for crossover and reproduction. Crossover or recombination is a process where two or more parents produce children solutions. It is expected that the operation may produce better offspring. Not all of new populations come from crossover and mutation, there is another process called reproduction which simply clones individuals selected by selection process [12]. The number and position of crossover points or nodes are randomly selected. The crossover mechanism is demonstrated in Figure 3.

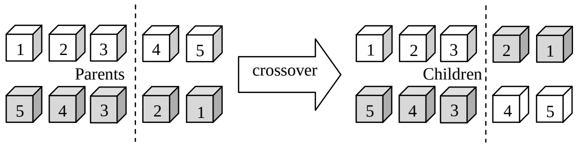

Figure 3 Crossover mechanism

Mutation role is to recover lost genetic materials as well as disturb the genetic information. The process is important because it can prevent solutions to be trapped in local optima. It is able to maintain the diversity in the search space and, therefore, can prevent premature convergence and stall evolution to some degree [12]. The parameters of the randomly chosen genes can be randomly changed to an integer ranging from 0 to 9 or other numbers depending on the encoding mechanism [5].

4.2 Genetic Programming

Although GA has been successfully developed, the algorithm alone can only optimise coefficients of a fixed control law structure and, hence, global optimum control system may not be attained. GP role is to widen the search space by introducing variable structure with mutation. However, the new structures are able to demonstrate their full potential only when the coefficients are tuned so a combination of GA and GP will be employed. Only the initial population and evaluation stages are different from those of GA and, hence, other processes will be omitted. There are several ways to create initial tree structure which is a usual initial population form for GP. However, these types of structure may be too complex and, hence, not effective for PID structure because the possible mathematical operation is just a plus and minus. In evaluation stage, GP can obtain the fitness values for each structure after their parameters are tune so it has to execute GA first and fitness values can be achieved from there.

5. Design

5.1 Aircraft model

A multi-role, all-weather fighter aircraft, F-16, will be used. The aerodynamic data is obtained from [10]. In order to construct the model to be as realistic as possible, a number of other models are incorporated. For example, the engine of F-16 is an afterburning turbofan jet so throttle gearing and engine power level lag are taken into account. The control surfaces of the aircraft are driven by servo-controlled actuators so these actuators are modelled as a first-order low-pass filters and different saturation limits and deflection rates. Also, the thrust response is modelled with a first-order lag.

5.2 Genetic Algorithm and Genetic Programming

The mechanism proposed by McGookin [8] is used in the GA to encode the chromosome. However, the range of possible solutions from this encoding is too wide so the value of the last term in the encoder is needed to be altered (see Figure 2). It is found that if the value 3.5 is changed to 4.0228, the range of the solutions can be reduced to 0 and 30. For GP to generate PID structure, only a string of genes which can be 0, 1 or -1 can be regarded as more effective than tree and other complex structures. As a result, the program can only produce the mathematical expression illustrated in the following equation.

$$\delta_e = \pm k_1 u_1 \pm k_2 u_2 \pm \cdots \pm k_7 u_7 \qquad (1)$$

where δ_e , k and u are elevator deflection, constant and input signal, respectively. There are 7 parameters that are fed to the controller, namely, $(h - h_{ref})$, $(\int h - \int h_{ref})$, $(\dot{h} - \dot{h}_{ref})$, V, $\dot{V}$, θ and $\dot{\theta}$, where h, V and θ are altitude, velocity and pitch angle, respectively so, for example, the first term is simply a difference between the altitude reference and response. As a result, there are 7 coefficients to be optimised and these coefficients are for the optimisation of longitudinal control law with disturbances. When the other controllers are incorporated three more coefficients are added: $|\psi - \psi_{ref}|$, $|\int \psi - \int \psi_{ref}|$ and $|\dot{\psi} - \dot{\psi}_{ref}|$, where ψ is yaw angle. For lateral controller, there are four coefficients altogether: φ, $\int \varphi$, $(\psi - \psi_{ref})$, $(\int \psi - \int \psi_{ref})$, where φ is roll angle. The parameters for the control law of the rudder includes θ and $\int \theta$. It should be noted that not all terms will be included since GP will decide when perform search process which variables and combination lead to more efficient control law. Figure 4 illustrates a possible combination of 4 variables constructing a control law.

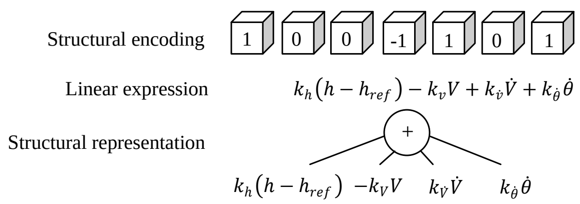

Figure 4 Structural encoding mechanism

The fitness function is basically the F-16 model. The model is executed programmatically and returns the integral of absolute error (IAE) as the fitness associated with the input coefficients. The IAE can be written as follows:

$$IAE = \int (|e(t)_1 + \cdots|)\, dt \qquad (2)$$

For the altitude hold with disturbances, there are two sources of error or $e(t)$ in current state: first is the difference between the altitude reference and response, and the second one is the differentiation of elevator deflection. However, when other controllers are incorporated, the IAE is modified to include the differentiation of aileron deflection, the difference between the ψ and ψ_{ref} and the difference between the actual position of the aircraft and the designated target.

5.3 Concerns on computational time

GA and GP are known to be computationally expensive; therefore, the programs should be developed in such a way that computational time is minimized. At first stage, it is found that executing the Simulink model in a for loop 100 times to evaluate population in each run takes 30.8 seconds compared with 18.9 seconds when executing only once by putting all possible solutions in the model and evaluate their fitness. Also, the number of command lines and for-loops are minimized as the program developed. For a run with 100 generations and population size of 100, the overall performance was substantially improved as the elapse time was reduced by half (4,447.9 compared with 2,216.6 seconds). It should be noted that the fitness of the population that is chosen for reproduction without crossover and mutation is not reevaluated to minimize the computational time. Nevertheless, the process is still very time-consuming.

The program can still be regarded as too computational expensive so Real-Time Workshop Technology in MATLAB was considered and implemented to make the aircraft model more efficient and, hence, and be executed faster. Previously, when executing the model, the trim state was not able to be obtained because the engine always produces negative thrust at first so the aircraft fluctuates to some degree before it stabilizes again. Hence, there is a need to trim the aircraft prior to the introduction of disturbance and, therefore, time-consuming. Simstate in MATLAB is incorporated in this version to hold the state parameters of the aircraft, including the engine so that the aircraft is trim prior to execution. In addition, parallel execution in for loop is introduced to utilize multi-processors to its full potential. With dual-core processors, it is found that the time to run 100 generations as described above take only 461.3 seconds.

6. Results

6.1 Altitude hold with disturbances

There are two types of disturbances: vertical wind gust and GPS error. An impulse wind gust is added in -Z direction for 1 second with a magnitude of 20 m/s after the aircraft is trimmed. The control law developed by GP is found to be:

$$\delta_e = 1.92(h - h_{ref}) + 0.06(\int h - \int h_{ref}) + 10.94(\dot{h} - \dot{h}_{ref}) - 0.01\dot{V} + 0.02\theta + 5.8\dot{\theta} \quad (3)$$

In order to determine the robustness of the control law, the optimised PID coefficients are implemented in the F-16 model incorporated with random vertical gust having varying velocity in the range from 0 to 40 m/s in -Z direction. The response is shown in Figure 5. The optimised PID obtained from GP can be regarded as quite efficient being able to withstand severe wind gust as the aircraft can still hovering around the holding altitude of 4,000 metres with ±30 metres amplitude.

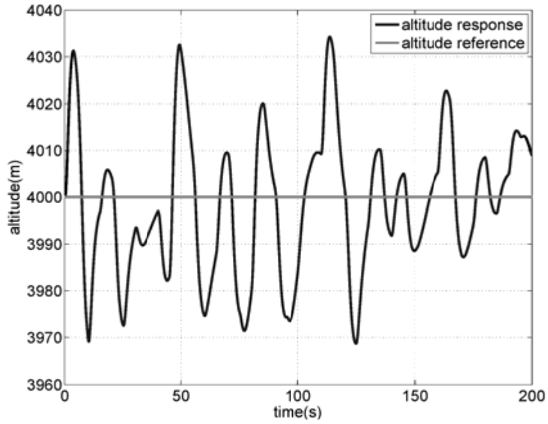

Figure 5 Aircraft's response to random vertical gust

It may be a good idea to examine how the aircraft will respond to impulse vertical wind gust with different magnitude. The F-16 will be run for 2,000 times with uniformly distributed gust with velocity ranging from -40 to -10 m/s and from 10 to 40 m/s in Z direction. The histogram of the fitness is illustrated in Figure 6 (top). It seems that the PID controller can act as a filter because although the input wind gust is uniformly distributed because there are a substantial number of runs that have fitness value of approximately 540.

The optimised PID coefficients, which are tuned with regard to the input impulse vertical wind gust, will be used because if the control law is effective enough, it should be able to handle different disturbance which is GPS altitude error in this case. The F-16 will be run for 2,000 times with uniformly distributed GPS error ranging from -100 to -3 and from 3 to 100 meters. The histogram of the fitness is demonstrated in Figure 6 (bottom). The fitness seems to vary from run to run; however, the overall picture of the fitness distribution has a resemblance with a normal distribution curve. Therefore, it can be concluded that although the control law was optimised according to the wind gust, it shows a satisfactory response when tested with other inputs which is GPS error in this case.

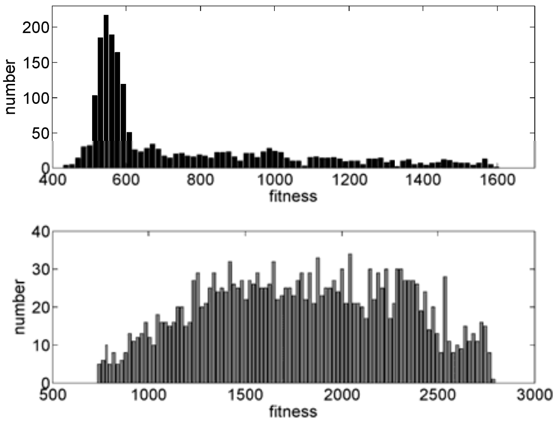

Figure 6 Histogram of the fitness with uniformly distributed impulse gust (top) and GPS error (bottom)

6.2 Altitude hold with guidance

Lateral controller, δ_a, is added to investigate whether the algorithm can find appropriate structure and optimise the coefficients of the control law for the aircraft to be guided to a desired position. The possible parameters that are fed to the elevator consist of the mentioned 7 parameters and the new three parameters, namely, $|\psi - \psi_{ref}|$, $|\int \psi - \int \psi_{ref}|$, $|\dot{\psi} - \dot{\psi}_{ref}|$. The parameters for the aileron are limited to only a fixed structure with 4 parameters in order to reduce the complexity and the search space. Also, the range of possible coefficients is limited to be within the range of 0 to 1. δ_r or directional controller is also added to minimize θ when banked angle is high and increase the stability of the aircraft. The designate position is set to be [3,000 1,500 -4,000]. Figure 7 illustrates the flight path and altitude response. The control law is found to be:

$$\delta_e = 0.04(\dot{h} - \dot{h}_{ref}) + 0.06V + 0.2\theta + 13.98|\psi - \psi_{ref}| + 0.01\left|\int \psi - \int \psi_{ref}\right| + 0.2|\dot{\psi} - \dot{\psi}_{ref}| \quad (4)$$

$$\delta_a = 0.02\phi + 0.00003\int \phi + 0.24(\psi - \psi_{ref}) + 0.01\left(\int \psi - \int \psi_{ref}\right) \quad (5)$$

$$\delta_r = 0.0001\theta + 0.02\int \theta \quad (6)$$

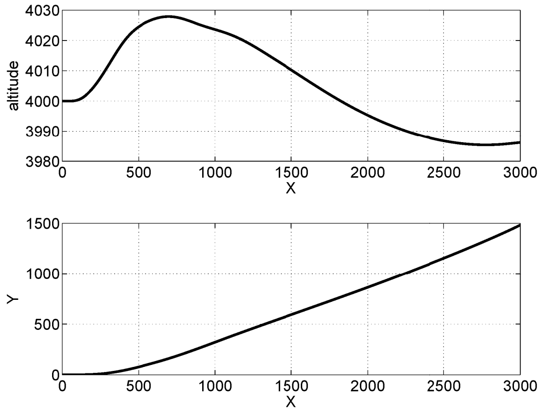

Figure 7 Flight path and altitude response of the aircraft flying to [3,000 1,500 -4,000]

6.3 Altitude hold with a banked turn

The GP is tested whether it can find the control law for the aircraft to perform a banked turn while holding the altitude. The turn diameter is set to 1,500 metres. The optimised control law is found to be:

$$\delta_e = 0.01(h - h_{ref}) - 0.02V - 0.004\dot{V} + 0.2\theta + 4.01|\psi - \psi_{ref}| + 0.12\left|\int \psi - \int \psi_{ref}\right| \quad (7)$$

$$\delta_a = 0.002\phi + 0.0002\int \phi + 0.02(\psi - \psi_{ref}) + 0.002\left(\int \psi - \int \psi_{ref}\right) \quad (8)$$

$$\delta_r = 0.70\theta + 0.01\int \theta \quad (9)$$

Figure 8 illustrates the flight path and altitude response. Although the altitude response of the aircraft fluctuates to a certain degree, the aircraft is able to effectively perform the banked turn.

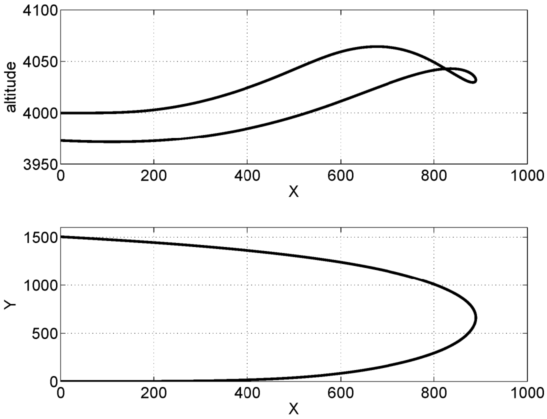

Figure 8 Flight path and altitude response of the aircraft flying to [0 1,500 -4,000]

7. Conclusions

The evolution algorithms can be regarded as an effective engineering tool in developing flight control system. A combination of GA and GP method has been implemented in this paper to tune PID coefficients and generate a simple control structure. Even though PID form is not always desirable, it is less computational expensive, more verifiable, more acceptable and more comprehensible.

Although, the GP has not been applied to its full capacity as the developed structure is substantially constrained to linear mathematical expressions with only two operators, it has been demonstrated that the optimised PID controllers are robust since it can withstand severe vertical gust and error from inaccurate GPS equipment in altitude hold mode. Also, the altitude gains and losses are minimised while the aircraft is guided to a designated position and while performing a banked turn. This means that the designed control law is quite robust because it ensures stability, satisfies the objectives and can handle more severe and other disturbances that it is not optimised against. Thus it leads to more robust performance and results in reduced pilot work load and accidents caused by human factors could be minimised with the developed automatic control system.

The major drawback of GP optimization is computational time, so it is important to develop a method which will allow to minimize the search within design space. Thus – ideally – GP will operate within the design space and build the control system in an optimally structural way to reduce the number of control parameters to only important ones.

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