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Autolanding of Commercial Aircrafts by Genetic Programming

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Abstract—**The genetic programming approach is applied to the problem of aircraft autolanding, subject to wind disturbances. The derived control law is tested successfully, using a linearised model of a commercial aircraft. The evolutionary control of autolanding is done within the desired operational envelope.**

Keywords: autolanding, aircraft, genetic programming, intelligent control, evolutionary control

1 Introduction

The limitations of classical control theory has led to the usage of computational intelligence techniques (neural networks, evolutionary algorithms, fuzzy logic) over the past two decades. Such techniques are also referred to as "intelligent control". Research in intelligent control aims in the derivation of control laws for which no control regimes are known, and the plant operation over large ranges of uncertainty [10]. Uncertainty can be attributed to noise and variations in parameters values, the environment and the inputs.

Traditional adaptive control, also aims in the controller's operation under uncertainty. However, intelligent controllers must be able to operate well, even when the level of uncertainty is substantially greater than that which can be tolerated by traditional adaptive controllers [2, 8].

Genetic programming (GP) offers an ideal candidate for the derivation of controllers, since its individuals in a population can be directly mapped to control laws. However, GP has only been applied so far to a small number of challenging control problems.

Autolanding has been included in the set of challenging control problems which researchers have to address, in order to explore new ideas for building automatic controllers [1].

This paper describes the application of genetic programming to the control of autolanding for commercial aircrafts subject to wind disturbances. The paper is organised as follows. Section 2 provides background information on the autolanding problem, while Section 3 details the commercial aircraft model used for the simulations. Section 4 describes the genetic programming approach for autolanding. Finally, Section 5 presents the conclusions for this work, and outlines current work in progress and future research.

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2 The Autolanding Problem

The safe landing of an aircraft requires the control of the aircraft so that its wheels make a comfortable contact with the ground within the paved surface of the runaway. Additional constraints in the kinematics of the airplane (described in detail in Section 3) have to be satisfied [9].

Most commercial aircrafts are equipped with an automatic landing system (ALS), also known as autolander. The autolander relies on the Instrument Landing System (ILS) which is airport based. The ILS guides the aircraft into the appropriate height and approach angle during landing [4].

Typically, commercial aircrafts include two feedback controllers, an autothrottle and a pitch autopilot. The descent of the aircraft is controlled by specifying the desired elevator angle θ_c (the output of ALS) to the pitch autopilot. The speed of the airplane is maintained constant by the autothrottle [1].

Inputs to the autolander control system include the altitude of the aircraft, its vertical speed and the desired values of these variables obtained from ILS. The ILS calculates an appropriate trajectory, and it is the responsibility of the controller (ALS) to generate a sequence of desired elevator angles $\theta_c(t)$, which will lead the aircraft to a touchdown on the runway within the given ranges of horizontal position, speed and pitch.

Current autolanding systems work reliably only within a specific operational safety envelope. The Federal Aviation Administration has set these limits to headwinds of less than 25 knots (28.75mph), crosswinds of up to 15 knots and tailwinds up to 10 knots. In addition, a moderate turbulence should be present and wind shear of 8 knots per 100 feet from 200 feet to touchdown [3]. Outside these operation envelopes, the ALS has to be disabled and the pilot has to take over [6].

Therefore, it is desirable to produce new autolanding controllers which expand the operation envelope, and generate safe control responses $\theta_c(t)$ under a wider range of conditions.

Previously, intelligent control approaches have been attempted to utilise neural networks for the autolanding problem [5, 6]. Here, the capabilities of genetic programming are investigated in this challenging problem.

3 Equations of Motion for the Autolanding Problem

A linearised model of a commercial aircraft [1] was used, for all the simulations described in the paper. Despite the usage of the linearised model, the model responds in a realistic way to the environment and the control parameters. In addition to that, data and conventional control system designs were included in the model, to provide a realistic representative problem [4]. The linearised model represents the motion in the longitudinal and vertical planes.

The equations of motion for the commercial aircraft are given by the following [1]:

$$\begin{aligned}
u(t+1) &= u(t) + \Delta\{X_u(u(t)-u_d) + \\
&\quad X_W(w(t)-w_d) + X_q q(t) - \\
&\quad g\cos\gamma\theta(t)\frac{\pi}{180} + X_e\delta_E + X_T\delta_T\} && (1)\\
w(t+1) &= w(t) + \Delta\{Z_u(u(t)-u_d) + \\
&\quad Z_W(w(t)-w_d) + (Z_q - U_0\frac{\pi}{180})q(t) + \\
&\quad g\sin\gamma\theta(t)\frac{\pi}{180} + Z_E\delta_E + Z_T\delta_T\} && (2)\\
q(t+1) &= q(t) + \Delta\{M_u(u(t)-u_d) + \\
&\quad M_w(w(t)-w_d) + M_q q(t) + \\
&\quad M_E\delta_E + M_T\delta_T\} && (3)\\
\theta(t+1) &= \theta(t) + \Delta q(t) && (4)\\
\dot{h} &= U_0\theta(t)\frac{\pi}{180} - w(t) && (5)\\
h(t+1) &= h(t) + \Delta\dot{h} && (6)\\
V_g &= U_0\cos\gamma + u_{gc} && (7)\\
x(t+1) &= x(t) + \Delta V_g && (8)
\end{aligned}$$

where u is the longitudinal velocity of the aircraft (ft/sec), w is its vertical velocity, q is the pitch rate (degrees/sec), θ is the pitch angle, h is the altitude (ft), and x is the horizontal position as negative of ground distance to desired touchdown position (ft). Δ is the sampling interval and it is set to 0.01sec.

The incremental elevator angle δ_E (degrees, set by the pitch autopilot) is given by:

$$\delta_E = \begin{cases} K_1(\theta_c(t)-\theta(t)) - K_2 q(t), & h(t) \geq h_f \\ K_3(\theta_c(t)-\theta(t)) - K_4 q(t), & h(t) < h_f \end{cases} \quad (9)$$

while δ_T is the autothrottle setting (ft/sec):

$$\delta_T = K_5(u_c - u(t)) + K_5\omega u_T(t) \quad (10)$$

and u_T is updated by:

$$u_T(t+1) = u_T(t) + \Delta(u_c - u(t)) \quad (11)$$

The terms related to wind disturbances are given by the following equations:

$$u_{gc} = \begin{cases} -u_h(1+\ln(\frac{h(t)}{510})/\ln 51), & h(t) \geq 10 \\ 0, & h(t) < 10 \end{cases} \quad (12)$$

$$\begin{aligned}
u_d &= u_{d1}(t) + u_{gc} && (13)\\
\alpha_u &= \begin{cases} \frac{U_0}{100\sqrt[3]{h(t)}}, & h(t) > 230 \\ \frac{U_0}{600}, & h(t) \leq 230 \end{cases} && (14)\\
u_{d1}(t+1) &= u_{d1}(t) + \Delta(\frac{0.2|u_{gc}|\sqrt{2\alpha_u}N_1}{\sqrt{\Delta}} - \\
&\quad \alpha_u u_{d1}(t)) && (15)\\
\alpha_w &= \frac{U_0}{h(t)} && (16)
\end{aligned}$$

$$\sigma_w = \begin{cases} 0.2|u_{gc}|, & h(t) > 500 \\ 0.2|u_{gc}|(0.5+0.00098h(t)), & h(t) \leq 500 \end{cases} \quad (17)$$

$$\begin{aligned}
w_d &= \sigma_w\sqrt{\alpha_w}(\alpha_w w_{d1}(t) + \sqrt{3}w_{d2}(t)) && (18)\\
w_{d1}(t+1) &= w_{d1}(t) + \Delta w_{d2}(t) && (19)\\
w_{d2}(t+1) &= w_{d2}(t) + \Delta(\frac{N_2}{\sqrt{\Delta}} - \alpha_w^2 w_{d1}(t) - \\
&\quad 2\alpha_w w_{d2}(t)) && (20)
\end{aligned}$$

where N_1, N_2 are random variables from the standard normal distribution.

The desired altitude h_c and the desired altitude rate of change $\dot{h}_c$ are calculated by the following:

When $h(t) > h_f$:

$$\begin{aligned}
h_c &= x(t)\tan\gamma && (21)\\
\dot{h}_c &= V_g\tan\gamma && (22)
\end{aligned}$$

When $h(t) \leq h_f$ and $h(t-1) > h_f$:

$$\begin{aligned}
\dot{h}_f &= \dot{h} && (23)\\
x_{c0} &= x(t) && (24)
\end{aligned}$$

When $h(t) \leq h_f$ and $h(t-1) \leq h_f$:

$$\begin{aligned}
\tau_x &= -\frac{h_f V_g}{\dot{h}_f - \dot{h}_{TD}} && (25)\\
h_c &= h_f\left(\frac{\dot{h}_f e^{-(x(t)-x_{c0})/\tau_x} - \dot{h}_{TD}}{\dot{h}_f - \dot{h}_{TD}}\right) && (26)\\
\dot{h}_c &= -\frac{h_f V_g \dot{h}_f e^{-(x(t)-x_{c0})/\tau_x}}{\tau_x(\dot{h}_f - \dot{h}_{TD})} && (27)
\end{aligned}$$

where $\dot{h}_{TD} = -1.5$ft/sec is the desired altitude rate of change on touchdown.

The constraint for the desired elevator angle θ_c (i.e. the controller's output) is:

$$-10^o \leq \theta_c \leq 5^o \quad (28)$$

The values of the various constants used in equations (1)–(27) can be found in Tables 1–3.

Aircraft Response		
X_u -0.038	X_w -0.0513	X_q 0.00152
X_E 0.00005	X_T 0.158	Z_u 0.313
Z_w -0.605	Z_q -0.0410	Z_E -0.146
Z_T 0.031	M_u -0.0211	M_w 0.157
M_q -0.612	M_E 0.459	M_T 0.0543

Table 1: Aircraft response parameters used for the equations of motion for the autolanding problem.

Autopilot and Autothrottle	
K_1 2.8	K_2 2.8
K_3 11.5	K_4 6.0
K_5 3.0	ω 0.1

Table 2: Autopilot and autothrottle parameters used for the equations of motion for the autolanding problem.

Other parameters	
u_c $0ft/sec$	throttle command
u_h $20ft/sec$	wind speed at 510ft altitude
U_0 $235ft/sec$	nominal speed
γ -3^o	flight path angle
h_f $45ft$	altitude at which flare begins
g $32.2ft/sec^2$	acceleration due to gravity

Table 3: Additional parameters used for the equations of motion for the autolanding problem.

4 The GP Approach

A plain GP was applied for the autolanding problem, based in the equations of Section 3. The goal was to derive a control law which autolands the aircraft. A successful touchdown is defined by the following ranges for the aircraft's vertical speed, horizontal position, pitch and horizontal speed [1]:

$$-3 \leq \dot{h} \leq -1 \quad (ft/sec) \quad (29)$$

$$-300 \leq x(T) \leq 1000 \quad (30)$$

$$-10 \leq \theta(T) \leq 5 \quad (31)$$

$$200 \leq V_g \leq 270 \quad (32)$$

where T is the time that landing occurs.

The controller for which GP searches for, requires four inputs: the current altitude h, the current altitude rate of change $\dot{h}$, the desired altitude h_c and the desired altitude rate of change $\dot{h}_c$. The single output is the desired elevator angle θ_c. Such a controller is shown in Figure 1.

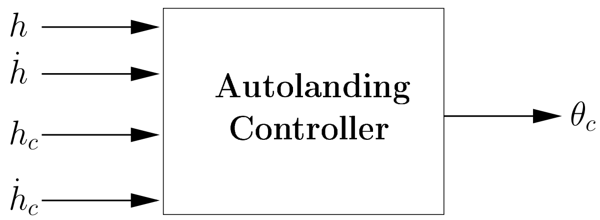

Figure 1: The controller structure for the autolanding problem.

The control signal θ_c is applied to the plant at intervals of 0.1sec, i.e. ten times as long as the sampling interval Δ used for the equations of motion of the aircraft. This means that θ_c is applied at $t = 0, 10, 20, \ldots$, and for other values of t, $\theta_c(t) = \theta_c(t-1)$.

The fitness function used by the GP runs was:

$$F = p_1^2 + p_2^2 + p_3^2 + p_4^2 \quad (33)$$

The four terms p_1, p_2, p_3, p_4 correspond to the four different measures that a successful autolanding is achieved, as defined by equations (29)–(32).

The value of term p_n, $(n = 1, 2, 3, 4)$ corresponding to a particular performance measure, is zero (0) if the GP individual lands the plane within the given range for that performance measure, otherwise it is equal to the distance from the closest bound of the range which it missed. The distances from the relevant bounds are normalised, so as to take into account the different values in the ranges used for $\dot{h}, x, \theta, V_g$.

The following terminal and function set were used:

Terminal set: $T = (h, \dot{h}, h_c, \dot{h}_c, R)$

Function set: $F = (\sin, \cos, +, -, *, /, pow)$

where R is the random number generator, / is the protected division as defined by [7], and pow is the power function taking as arguments the base and the exponent.

The GP parameters used, are shown in Table 4.

The initial conditions for all the simulations runs were:

$$u(0) = w(0) = q(0) = \theta(0) = 0 \quad (34)$$

$$x(0) = \frac{h(0)}{\gamma} \quad (35)$$

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population size	1000
crossover probability	0.90
reproduction probability	0.10
mutation probability	0.00
P of function crossover	0.90
maximum initial depth	6
maximum allowed depth	17
generative method	ramped half-and-half
selection method	fitness proportionate

Table 4: GP Parameters for the Aircraft Autolanding problem.

$$h(0) = 500 \tag{36}$$

$$u_T(0) = 0 \tag{37}$$

$$u_{d1}(0) = w_{d1}(0) = w_{d2}(0) = 0 \tag{38}$$

A number of different runs were made, subject to different N_1, N_2 (as defined in Section 3). Runs with different N_1, N_2 correspond to different fitness cases. To do so, a different seed was used for the random generators calculating N_1 and N_2. However, the wind speed u_h (speed at 510 ft altitude) was set to be 20ft/sec in all cases.

GP managed to find an individual (controller) which successfully lands the model of Section 3.

5 Conclusions and further research

The GP approach is tested in a control problem, the autolanding of a commercial aircraft, which is included in the set of challenging control problems for computational intelligence techniques [10]. A control law which successfully lands the aircraft subject to wind disturbances was found.

Current work in progress examines whether this individual control law (or other control regimes derived by GP) can autoland the same plant, subject to wind disturbances of greater magnitude, so as to increase the operational envelope of the autolander.

Future research should compare the results of this approach with the results obtained by neural networks approaches. Additional work is also required, aimed at the investigation of whether any of the derived controllers can be proven to be stable by theory.

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