GA tuning of Pitch Controller for Small Scale MAVs

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Abstract: - The paper presents the application of intelligent tuning methods for the control of a prototype MAV in order to address problems associated with bandwidth limited actuators and gust alleviation. Specifically, as a proof of concept, the investigation is focused on the pitch control of a MAV. The work is supported by experimental results from wind tunnel testing that shows the merits of the use of Genetic Algorithm (GA) tuning techniques compared to classical, empirical tuning methodologies. To provide a measure of relative merit, the controller responses are evaluated using the ITAE performance index. In this way, the proposed method is shown to induce far superior dynamic performance compared to traditional approaches.

Key Words: - **MAV, Intelligent control, Genetic Algorithms**

1 Introduction

In its most general role, a small-scale MAV, as considered here, is an aircraft that will ultimately act independently from humans to perform tasks such as surveillance or package delivery. To date, most uses of MAVs have been for military purposes, however, relatively low-cost vehicles are now encroaching into commercial, industrial and scientific markets for purposes of crowd monitoring, data gathering [6], and load transportation, for instance [1]-[7]. Nevertheless, whilst such vehicles often present a cost-effective and unobtrusive solution to what might otherwise be a labour intensive or costly technology driven task, problems with deployment in all-weather conditions ultimately limit their value. Typically, careful planning of the flight envelope is necessary to avoid detrimental meteorological conditions. This problem is accentuated as the MAV size reduces, then typically requiring higher-lift plan-forms that leave it susceptible to gust disturbances or thermal updrafts, for instance, leading to possible collision or uncontrolled descents. Such problems can be ameliorated to some degree by the use high bandwidth flight control surface actuators. However, typically, low cost servos or stepper motors to actuate small control surface areas are used for commonly encountered non-military vehicle variants. Moreover, the use of low-cost actuators can significantly limit the dynamic capability of the MAV, and, in many instances, physical rate limits on the flight control surfaces, by virtue of using motors which themselves are effectively rate-limited, (PWM excited stepper units for instance), can induce substantial degradations in performance when large control actions are necessary, and, ultimately induce instability.

Here then, a GA is employed to improve the transient performance of a low-level surveillance MAV when subjected to pitch angle gust disturbances, see Fig. 1, and limited bandwidth actuators. Optimising a feedback controller for such a demanding application is complicated by the aircrafts small size and limited actuator response leading to complex interacting non-linear dynamics.

Figure 1 MAV

2 MAV dynamic model and control objectives

The dynamic characteristics of the MAV, constrained to motion about the pitch axis, is described by the state-variable model in (1),

$$\begin{bmatrix}\Delta\dot{U}\\ \Delta\dot{W}\\ \Delta\dot{q}\\ \Delta\dot{\theta}\end{bmatrix} = A\begin{bmatrix}\Delta U\\ \Delta W\\ \Delta q\\ \Delta\theta\end{bmatrix} + B\left[\Delta\delta_e\right] + A'\begin{bmatrix}U_g\\ W_g\\ q_g\end{bmatrix} \qquad (1)$$

where $\Delta\delta_e$ is the elevator deflection about the trim point, U_g, W_g, q_g, are effective gust velocities, A' describes the impact of the gusts on the states, and,

$$A = \begin{bmatrix} -0.8013 & 0.3303 & 0 & -9.81 \\ -2.4467 & -14.6 & 12 & 0 \\ 0.1212 & -0.1675 & -1.22 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} -0.06875 \\ -3.792981 \\ -39.739 \\ 0 \end{bmatrix} \qquad (2)$$

$$C = \begin{bmatrix} 0 & 0 & 0 & 1 \end{bmatrix}$$

2.1 Controller design methodology

The objective for the controller design methodology is to remove complexity and subjectivity by describing how a genetic algorithm (GA) can be employed to choose classical 3-term PID controller parameters based on the evaluation of the integral of time absolute error (ITAE) criterion. Initially, the controller parameters are determined by the designer to ensure stable operation. The GA is then employed to search a parameter space ±1 order of magnitude of the initial values to obtain a controller with the best ITAE. Thus, the designer subjectively provides a best guess that is subsequently refined by the GA.

It is widely accepted that GAs provide an extremely useful tool for use in optimization problems owing to their ability to search a wide parameter space with minimal effort over a highly non-linear multi-dimensional surface featuring multiple local minima; problems where traditional gradient-based methods often fail. Thus, GAs have been employed in a multitude of applications as diverse as optimizing orders for a reheat furnace, to the design of permanent magnetic 3-phase motors (with varying degrees of success) [16], [17].

In general terms, genetic algorithm refers to an iterative search technique based on Darwinian ‘survival of the fittest’ principles. GAs can take many guises. The most popular is a form that involves evaluating a population of candidate solutions (called chromosomes), which are then ranked in order of ‘fitness’ using a suitable cost function. Subsequently, solutions with the best fitness rankings are selected for further investigation. This involves perturbing their parameters in a pre-determined manner to permit further exploration of the search space. Once a new set of population parameters has been generated, the evaluation, ranking and perturbing processes are re-iterated. Usually, several generations (iterations of the searching/evaluation process) are required before the GA converges towards a solution. Figure 2 illustrates the structure of a typical algorithm.

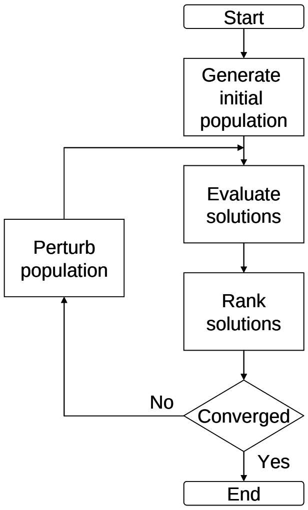

Figure 2 Iterative structure of the GA

2.2 Implementation of on-line GA tuning

For ease of implementation, a DSPACE hardware development platform is employed for this investigation. Owing to the floating-point precision provided by the DSPACE controller number representation, it is necessary to use a continuous value variable to represent controller parameters. In its most basic form, therefore, a single chromosome, which represents one candidate solution, is defined using an array of 3 variables. The initial population for the GA is determined using a random number generator to perturb the designer’s ‘best empirically tuned’ controller by ±1 order of magnitude. Although the effects of the candidate controller parameters are evaluated experimentally using the test setup described in section 3.1, the ITAE cost function (3) is accurately determined using the DPSACE system. The ranking process involves sorting ITAE values in order of magnitude. Since ITAE is directly proportional to error, lower values are ranked more favorably.

$$\text{ITAE} = \int_0^T \left(t \times |error|\right) dt \qquad (3)$$

The perturbation process is divided into 2 distinct stages viz. breeding and mutation. In the breeding stage, a new population is generated from the top 50% of the existing population. A process known as tournament selection is employed to choose two parent chromosomes, p_1 and p_2, based on the ITAE ranking [18]. Subsequently, the chromosomes of each parent are combined in such a manner to form two children that are then placed in the new population. The combination process uses a random number generator to select the proportion of each parent that is transferred to the child. By way of example, if p_1 and p_2 are single parameter chromosomes then their 'children' c_1 and c_2 are formed from the random number α as follows:

$$\begin{aligned} c_1 &= \alpha p_1 + (1-\alpha) p_2 \\ c_2 &= (1-\alpha) p_1 + \alpha p_2 \end{aligned} \qquad (4)$$

The children from this process are used to replace the poorer chromosomes in the population, hence, the term 'survival of the fittest'. Justification for using this strategy is that the children should inherit some desirable attributes from their parents. For the first iteration, a randomised population is used. However, subsequent iterations refine the population and, ultimately, it should converge. For the first few generations breeding allows a large parameter space to be searched. As the number of generations increases, more of the chromosomes in the population will begin to resemble one another; thereby permitting desired characteristics to be retained.

Employing such 'breeding' strategies alone as part of the perturbation process often leads to convergence towards only local minima. To ensure this does not happen, and also in an effort to further explore more of the search space, the chromosomes are modified using a mutation process. For this investigation, this is achieved by randomly replacing a parameter in a chromosome with a random number. The random processes involved in the breeding and mutation stages are determined by a uniform random number generator. A mutation rate of 50% is employed.

3 Experimental Setup

For reasons of repeatability, the UAV is mounted close to its centre of pressure onto a test frame to restrict its movement to the pitch axis, see Fig. 1. Pitch angle measurements are employed by the 3-term compensator to provide closed-loop control of the UAVs dynamic response, and for evaluation of the ITAE cost function. Although, the work presented in this paper focuses on elevator control optimisation, the UAV is equipped with all the actuators and batteries required for true flight. However, for consistency and repeatability, the UAV is powered from a stabilised DC power supply to alleviate anomalies associated with varying battery state-of-charge.

3.1 Experimental procedure

The UAV test set-up is placed in an open-end wind tunnel that provides a disturbance free laminar flow of 4m/s for this investigation. The UAV is set to horizontal trim. The aircraft is then taken away from its trim point by 'forcing' a steady-state out-of-trim disturbance on the pitch angle of ~30^o. The disturbance is released and the aircraft's controller action to steady state is recorded as ITAE. The ITAE results are used as the 'cost' criteria in the GA tuning methodology.

4 Experimental Results

For both experienced and inexperienced designers of 3-term compensators, the controller may typically be tuned in the following empirical manner:

i) Find an acceptable proportional gain which provides some overshoot but no sustained oscillatory behaviour.
ii) Select an integral gain that eliminates steady state error whilst not unduly affecting stability.
iii) Finally, the addition of derivative gain to improve damping whilst not unduly increasing noise.

This procedure for empirically tuning a 3-term controller for the pitch axis of the MAV considered here, proved to be largely unsuccessful. By way of example, the range of proportional gain failed to radically improve on the natural oscillation when returning from a pitch deflection, as evidenced by the transient results shown in Fig.3, which shows transient responses from an initial deflection of nearly 30^0, as might be expected in response to wind gust. Specifically, transient responses with proportional gains of ($K_p=0$), $K_p=-0.1$ and $K_p=-1.0$

are shown. Moreover, further experimentation showed that further increase in the value of K_p did not enhance performance.

Replacing the proportional controller with integral action also proved to be difficult to tune empirically. By way of example, from Fig. 4, which shows transient responses for K_i=-0.8 and K_i=-3, it can be seen that little or no enhancement is evident compared with the proportional controller case. However, by comparing the gradients of the oscillatory transients in Figs. 3 and 4, it is evident that rate limiting of the actuators is present, thereby inducing integral-windup (no active anti-windup mechanism was employed for these tests) in the latter case.

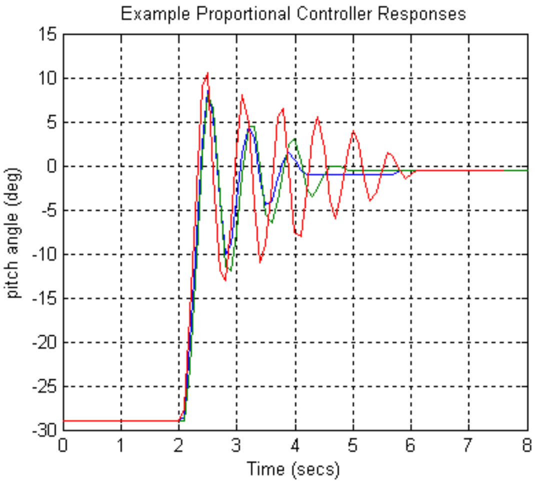

Figure 3 Experimental Transient Responses-Proportional controller only

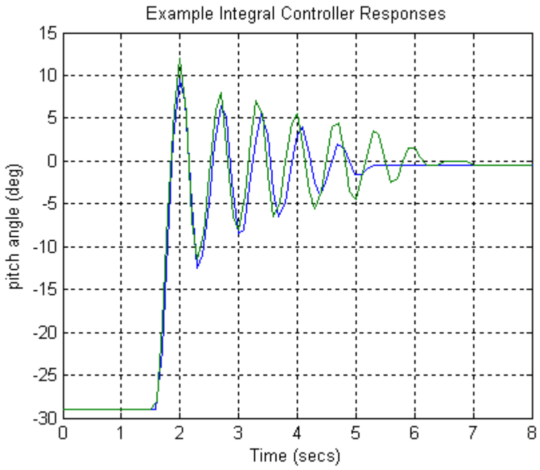

Figure 4 Experimental Transient Responses-Integral controller only

Extensive on-line trials to determine the 'best guess' gains for the 3-term controller, ultimately led to the 'acceptable' response given in Figure 5. It can be seen that the addition of derivative action significantly enhances performance, as is commonplace in stability augmentation and tracking compensators for MAVs.

Specifically, Fig. 5 shows the response to deflection for controller parameters K_p=-0.1, K_i=-0.2 and K_d=-4.0. It clearly shows that the controller returns the MAV to trim within the test's 4-second time frame (timed from release from deflection). These parameters are taken intuitively from testing values across a range around a best result, or, in more general terms, a local minimum.

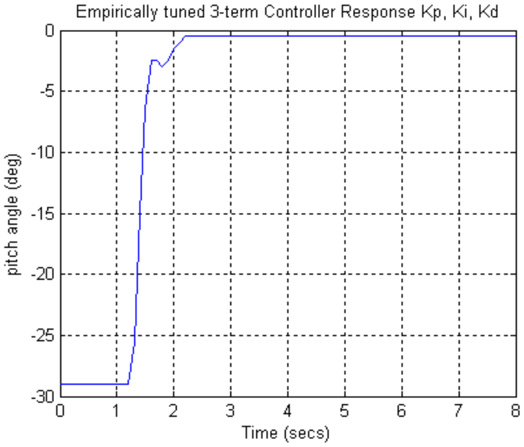

Figure 5 Experimental Transient Responses-PID

Nevertheless, when compared with the results from GA tuning of the controller parameters, as shown in Fig. 6, it is apparent that significant improvements can be made if the solution set is not constrained to local optima. The responses in Fig.6 employ controller gain values of K_p=-0.02003, K_i=-0.04975, K_d=-0.53049 and K_p=-0.01776, K_i=-0.06232, K_d=-0.70933, for the 5th and 7th generation results, respectively. By comparing the gains from all the the control structures, it is evident that those for the 'optimum' solutions are neither immediately intuitive nor easily discovered through testing at regular intervals. This, therefore gives a prime example of merits of the GA tuning methodology.

By consulting Table I, a comparison of the ITAE values associated with the 'best' transient responses presented in Figs. 3, 4, 5 and 6 shows that the GA indeed outperforms empirical tuning methods. Notably, the same actuator rate-limits were used throughout each test, thereby presenting a non-linear system for controller tuning purposes.

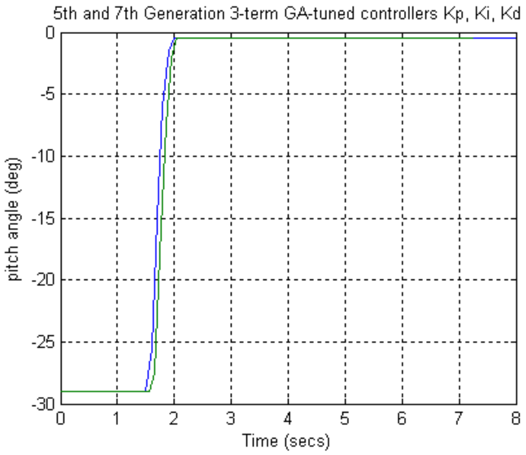

Figure 6 Experimental Transient Responses-GA tuning of PID, 5th and 7th generation results

Table I ITAE results for each controller type

	ITAE
Proportional control	0.14
Integral control	0.1
Empirically tuned PID	0.02
GA (PID)	0.011

5 Conclusions and Future Work

The paper considers the impact of bandwidth limitations on the performance of MAVs—specifically, the impact on the pitch dynamics of the vehicle when rate-limited actuators are employed. The use of Genetic Algorithms for the on-line tuning of the vehicle pitch controller, during wind tunnel testing, has demonstrated the merits of such techniques for the difficult task of robust controller design for these small vehicles. Although not explicitly considered here, the intelligent development of the control structure is currently being investigated using similar techniques. The results of this further investigation will be reported in due course.

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