Flight control system design for a micro aerial vehicle

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Abstract

Purpose – The purpose of this paper is to present an original design procedure for a flight control system.

Design/methodology/approach – An optimization process, based on a genetic algorithm (GA), is used to meet the frequency domain handling qualities requirements in the longitudinal plane for an unconventional platform characterized by nonlinear aerodynamics. The parameters are implemented in the search process as fitness functions related to the expected magnitude of bandwidth and delay for an existing micro aerial vehicle. The bandwidth and the delay of the longitudinal short-term attitude response are estimated before and after the inclusion of the flight control system in the simulation model, and the parameters are compared with the expected handling qualities levels. A qualitative analysis of handling qualities levels is also performed by implementing the augmented aircraft in a simulator with a realistic visual environment.

Findings – The results show that an optimal search process based on a GA can implement the handling qualities requirements with a computational procedure that is straightforward.

Research limitations/implications – Even if the requisites for bandwidth and delay implemented in the search process are general in use as no specific aircraft response type is taken as a reference for the estimation of handling qualities requirements, only future experimental work will provide insight for the definition of specific Level 1 boundaries for micro aerial vehicles in remotely piloted flight.

Originality/value – The virtual environment is useful to test remote piloting with unconventional onboard visual cues. This is important in applications in which technical limitations may preclude complete real time data link during flight tests in the first development phase of the vehicle.

Keywords Flight dynamics, Flight control, Aircraft industry

Paper type Research paper

Nomenclature

A	=	amplitude
$[\mathbf{A}]$	=	state matrix
$[\mathbf{B}]$	=	state matrix
$G()$	=	generic transfer function
GA	=	genetic algorithm
k_i	=	feedback gain ($i = u, w, q, \theta$)
$[\mathbf{K}_P]$	=	feedback matrix (proportional)
n	=	number of parameters (fitness function)
p, q, r	=	angular velocity components (body axes)
s	=	complex variable (Laplace transform)
T_1	=	time constant (lead compensator)
T_2	=	time constant (lead compensator)
u, v, w	=	velocity components (body axes)
$\bar{\mathbf{u}}$	=	control vector
V	=	airspeed
x	=	parameter (fitness function)
$\bar{\mathbf{x}}$	=	state vector

Greek symbols

δ_a	=	aileron stick control
δ_e	=	elevator stick control
$\Delta\phi$	=	phase lag
φ, θ, ψ	=	angles of roll, pitch and yaw (Euler angles)
ω	=	frequency
τ_P	=	phase delay

Subscripts

180	=	neutral stability point ($\Delta\phi = -180°$)
avg	=	average
BW	=	bandwidth
k	=	index
low	=	low frequency range
L	=	lower axis range
max	=	maximum
R	=	reference
U	=	upper axis range

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Introduction

The search of optimal solutions is a primary interest in the design of controllers (Delgado, 1997). Desired pole placement and eigenstructure assignment are conventional goals of the control design procedure. The performance of the controller may also be defined in terms of regions of interest instead of desired states. This is the case of aircraft handling qualities requirements. Stability, robustness, good command following, noise rejection and low sensitivity to model uncertainties are also significant concerns for the designer and their inclusion in the search process may be required to ensure adequate control performances.

The main types of search methods are considered in Goldberg (1989): calculus-based, enumerative and random. Calculus-based methods are local, i.e. the optimal conditions they search are the best in a neighborhood of the current point. They depend upon both the existence of derivatives and the continuity of the function to be maximized. This last point is a severe limitation in terms of robustness for several engineering applications. Enumerative methods seek the optimal solution by computing the objective function in every point of the search space. This makes the enumerative algorithms substantially inefficient and time consuming when applied to large domains of possible solutions. Random search is an alternative strategy that can bypass the limitations of the previous methods. The genetic algorithms (GAs) belong to this last family of solvers, as the random choice of the possible solutions is combined with criteria for the direction of search which derive from natural evolution of species. This technique is considered global and robust in terms of search over the space of solutions.

The GA (Goldberg, 1989) operates on the principle of the survival of the fittest. An initial population is created from a random selection of the parameters within the domain of acceptable solutions. Each individual is defined by a fixed number of parameters which are coded in a binary form (chromosomes). The allowable range of variation for each parameter is given. A fitness function is provided as a metric of performance of the individuals. The function is computed from the set of parameters which characterizes the single individual. No restriction is imposed on the continuity of the fitness function. A new generation of individuals is created by means of selection, crossover and mutation. Note that, differently from classical search methods, the transition rules from one solution to a new solution in the search space are not given in deterministic form but using probabilistic operators. Only the best individuals are selected for mating and the numerical algorithm determines the transmission of chromosomes from parents to children. Differently from the natural case, the size of the new population is kept constant and each new generation is expected to increase the average fitness. The search is interrupted when the evolution process is completed in terms of fitness. As a matter of fact, the evolution of the generations can be represented by the average of the fitness function of the population and/or by the performance of the best individual. As an alternative, the evolution process may be closed after a given number of generations.

Many types of engineering and aerospace related optimization problems in the area of controls can be solved using the GA approach: linear and nonlinear control systems design, adaptive gain tuning, gain scheduling selection and, generally, multiple objective optimization.

A standard linear quadratic regulator problem is optimized in Krishnakumar and Goldberg (1992) using a GA and the solution is compared with the traditional approach. In the same paper, a nonlinear windshear feedback controller optimization problem is also addressed using a simple GA.

A GA based technique is presented in Gray *et al.* (1995) that allows control system performances to be specified as constraints on the system time domain response. A detailed analysis of the impact of the mathematical form of the fitness function is also given. The authors show that the minimization of an error functions given by the least square sum of the error between the actual system response and the desired system response may lead to high gains and severe oscillations. The solution proposed is based on penalty functions (Homaifar *et al.*, 1994) to represent the constraints.

A GA in Gray *et al.* (1997) is adopted for the design of a network of linear controllers according to the operating point. The GA is used to optimize the gain scheduling and the activation range of the individual controllers.

A design optimization for a gain scheduled controller is given in Kramer and Martin (1996). The feasibility of the GA approach is demonstrated for a set of controllers for the longitudinal dynamics of an F-18 aircraft. The results are also compared with traditionally designed controllers in terms of time domain response.

A robust controller is designed in Mao (2002) for a helicopter in low speed forward flight by the use of H_∞ mixed sensitivity approach. The GA is used in the design process to optimize the weighting functions in order to search for the H_∞ controller which meets design specifications in both time and frequency domain. The design is based on the minimization of cost functions which depend on divergence from reference time and frequency domain responses (bandwidth and delay).

A synthesis technique, blended with multi-objective characteristics, for the design of structured specified μ-suboptimal PID controllers is presented in Kitsios and Pimenides (2003). The design, involving a super-maneuverable aircraft as an example, is based on a GA optimization approach and the resulting controllers ensure stability and nominal high performance for the entire operating range.

A pole placement technique is used in Ouyang and Qu (2002) to obtain adequate stability augmentation for an airship. Robustness requirements are also implemented in a cost function.

The design and the implementation of a full envelope nonlinear aircraft controller that includes stability augmentation, tracking control and flight-path generation is presented in Neidhoefer and Krishnakumar (2001). The design of the stability augmentation system is based on pole placement performed by a GA, which gives as an output of the search process, the appropriate gain matrices.

The review of references suggests that the design of control systems with the support of optimal search by means of a GA is feasible. In any case, the majority of the above mentioned applications are devoted to design system dynamics by means of pole placement and shaping of time domain response, taking the stability and the robustness of the control system as a primary problem. Differently, handling qualities are substantially related to the frequency domain response (Mitchell *et al.*, 2004). Furthermore, it can be observed that the implementation of handling qualities requirements in the design process is not straightforward and classical optimal control design tools may generally be inadequate for this purpose, as they may lead to a stable robust controller with unsatisfactory handling qualities. Note that the performance of the controlled system is evaluated in terms of regions of interest, as bandwidth and delay of the controlled system combined with other non homogeneous requisites which make gradient based search method harder to apply for the given case.

Within this area of interest, a research activity was started at Politecnico di Torino (Fantinutto *et al.*, 2005). In the present paper, a control design application for the MicroHawk micro aerial vehicle is discussed.

The MicroHawk (Pralio *et al.*, 2003) concept was designed within a European Union funded project (Micro Aerial Vehicles for Multi Purpose Remote Monitoring and Sensing Project), by a research group at Politecnico di Torino. It consists of a fixed wing, tailless integrated wingbody configuration, powered by a DC motor and tractor propeller (Figure 1). Three versions have been developed and tested,

Figure 1 The micro aerial vehicle configuration (MicroHawk)

characterized by different size and weight. A 150 mm wingspan platform – named MicroHawk150 – has been designed and developed for very short range, remotely piloted missions, characterized by low flight duration and narrow operating scenario. It has been equipped with basic on-board systems (DC motor, propeller, battery pack, controller, receiver and servos), for a total weight of approximately 35 g. The medium-sized platform – named MicroHawk300 – is characterized by a 337 mm wingspan; it weights about 100 g in the unequipped version. The MicroHawk300 has been developed to perform a basic reconnaissance mission, carrying a micro camera and/or sensors for remote monitoring and sensing. The larger vehicle – named MicroHawk600 – is characterized by a 600 mm wingspan and the bare platform weights 400 g. Its design has been mainly addressed to the need for higher payload weight fraction and larger internal volumes.

The MicroHawk600 version can potentially achieve autonomous flight as it is possible to locate onboard a commercial small size autopilot without exceeding wing loading limitations for hand launch. Differently, the MicroHawk300 version is unable to host a complete electronic navigation system. As a consequence, the application is limited to line-of-sight remote piloting. An attempt to extend its operating range has been performed using the onboard micro-camera as a visual reference for the pilot (Plate 1). The flight experiments confirm that remote control is possible without external 3D view of the micro vehicle, but handling qualities are degraded with an increase of pilot workload. This is the result of the large bandwidth response in the longitudinal plane typical of these inertially slender vehicles.

The handling qualities enhancement by means of a conventional flight control system is here attempted. The design problem is given in terms of short term handling qualities requirements and the search process is performed with a GA. The in-flight performances of the augmented vehicle are tested by comparing qualitative rating obtained during simulated flight sessions which reproduce aircraft dynamics and onboard camera view in a substantially realistic way, without risk of compromising the integrity of any flying prototype.

Present work

The objectives of this paper are to:

- include the frequency domain handling qualities requirements in the design procedure of a flight control system, in a form suitable for search and optimization by means of a GA;
- evaluate the feasibility of the design method for a nonlinear mathematical model of a fixed-wing micro aerial platform;
- verify the dynamic response of the augmented aircraft by implementing the flight control system in a realistic simulation model; and
- perform a qualitative comparison of handling qualities levels – with and without flight control systems – by means of a simulator.

Mathematical model

The simulation platform architecture consists of a high performance computer cluster connected by a digital bus, that handles the interactions among the mathematical model software, the scenario rendering engine, and the graphical user interfaces. The cluster consists of two personal computers, one dedicated to the mathematical model and to the rendering engine and the other for managing the virtual instrumentation panel. The graphics output is demanded to three LCD monitors. The user interacts with the system by means of keyboard, 3D joystick, and rubber pedals (Plate 2). The main software packages are represented by the aircraft/environmental mathematical model and the scenario rendering formulation. The former one consists of three sub-modules: the aircraft dynamics model, the propulsive system model and the atmospheric turbulence model. The rendering engine performs the visualization of a comprehensive scenario by means of textured altitude maps. A complete urban environment (houses, buildings, parking, roads, …) with in-flight collision detection is also enclosed in the virtual scenario. A bare Head-Up Display is also provided, showing the main information regarding flight parameters in digital format. The rendering engine allows to set a camera view – either internal or external – and a camera zoom. In the case of external view, the 3D aircraft model is visible and the user can change its point of view, by rotating around the vehicle during the simulation session. In addition, off-line data processing can be performed as the output data can be saved in a formatted file.

The mathematical model developed is a nonlinear representation of a single engine aircraft with rigid fuselage (Figure 2). No small angle assumption is invoked for aerodynamic angles of the vehicle and the aerodynamics of fuselage and stabilizers is modeled using static coefficients obtained by wind tunnel experiments for different angles of attack and sideslip. The effects of controls (elevator, aileron and rudder) are superimposed in terms of increments.

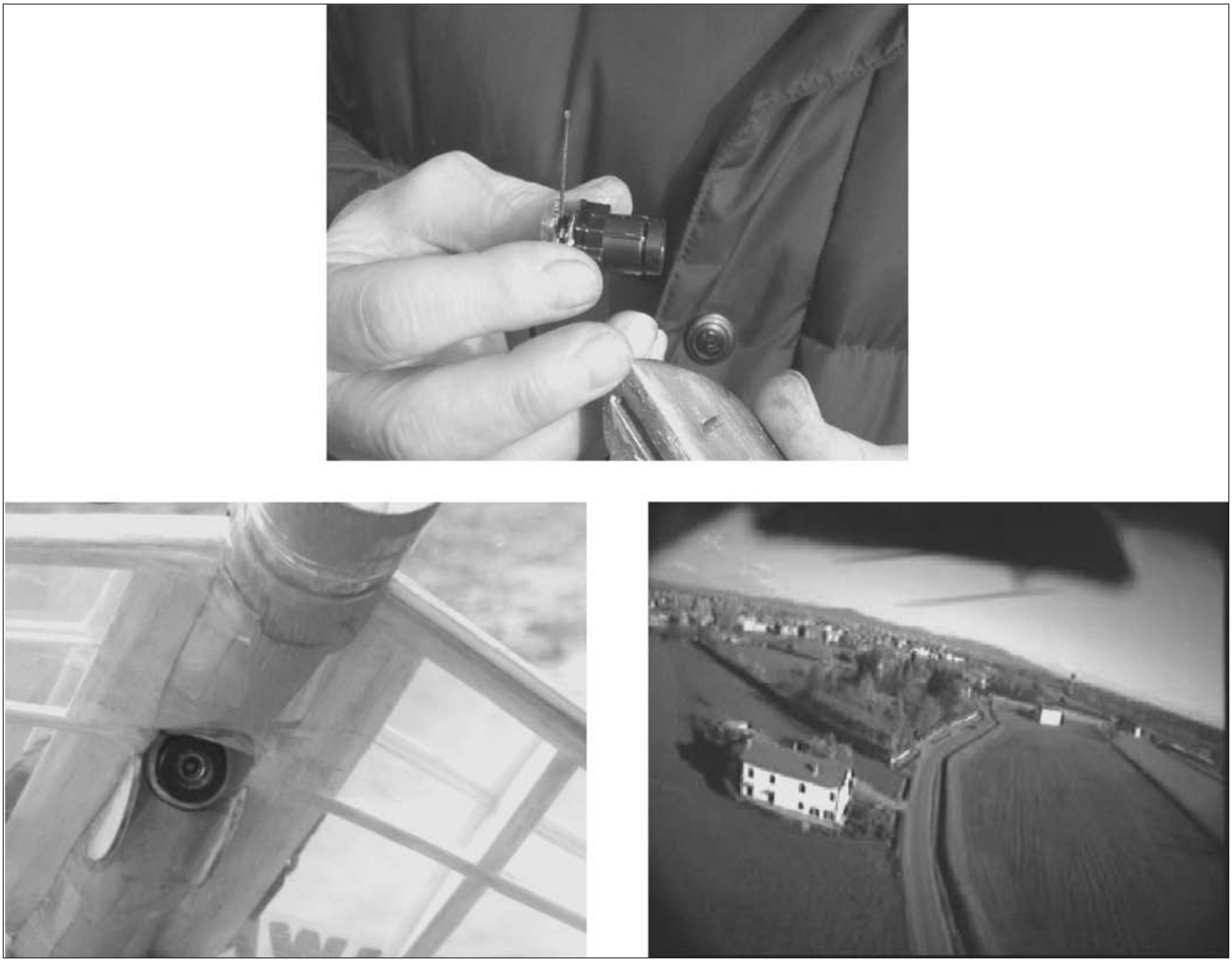
A propulsive system model based on DC motor and propeller was implemented. It consists of two parts:

1. the mathematical correlation between supplying voltage and current drain with engine operating rpm; and
2. the relationships between propeller rpm and thrust and torque coefficients.

Blade element theory, accounting for induced inflow, is applied to estimate propeller aerodynamics and performances. Thrust and torque characteristics are evaluated according to flight conditions, throttle settings and aerodynamic angles.

The rigid body motion of the aircraft is modeled using six nonlinear force and moment equations and three kinematic relations (Euler equations). The most important feature of

Plate 1 The in-flight video streaming from the micro aerial vehicle



this set of equations of motion is that the states need not to be small quantities; thus, all the kinematic nonlinearities associated with the motion of the rigid body are retained.

The order of the complete system is 9 and the state vector can be represented as $\bar{\mathbf{x}} = [uvwpqr\theta\phi\psi]^{\mathrm{T}}$ while the control vector is defined as $\bar{\mathbf{u}} = [\delta_e \delta_a \tau]^{\mathrm{T}}$. Note that MicroHawk control is accomplished using two elevons.

The primary control actuators are also included in the mathematical model and their dynamic response is represented by a second order transfer function.

The effects of atmospheric turbulence are optionally included in the present model (Anonymous, 1997), as the gust components are superimposed to the velocity components of the vehicle.

Initial values of altitude, airspeed, turn rate, sideslip and climb angles are given as inputs of the trim procedure, which is based on residual minimization. The algebraic equations enforcing force and moment equilibrium (9 equations) are combined with the additional kinematic equations (2 equations) that must be satisfied in steady flight or in a turn, and the combined system (11 equations) is solved simultaneously. The solution yields control and throttle settings, trim attitudes and rates of the entire aircraft.

The response to pilot inputs is obtained from direct numerical integration of the equations of motion and trajectory, starting from trim conditions.

A linearized set of small perturbation equations can be extracted from the non-linear model ($\dot{\bar{\mathrm{x}}} = [\mathbf{A}] \cdot \bar{\mathrm{x}} + [\mathbf{B}] \cdot \bar{\mathbf{u}}$). The coefficients of the state matrices **[A]** and **[B]** are derived numerically about the trim condition, using finite difference approximations. The linearization of the dynamic equations is carried out in the body fixed coordinate system. The state-space representation is also used for estimating the frequency response of the system.

An optional feedback control loop is implemented in the mathematical model adopted for the present study. A lead-lag compensator is included in order to tune aircraft transient dynamic response:

$$G(s) = \frac{1 + T_1 s}{1 + T_2 s}$$

and proportional feedback gains can be specified for each component of the state vector:

$$\Delta u(s) = [\mathbf{K}_{\mathrm{P}}] \cdot x(s)$$

Plate 2 The operational environment implemented in the simulator

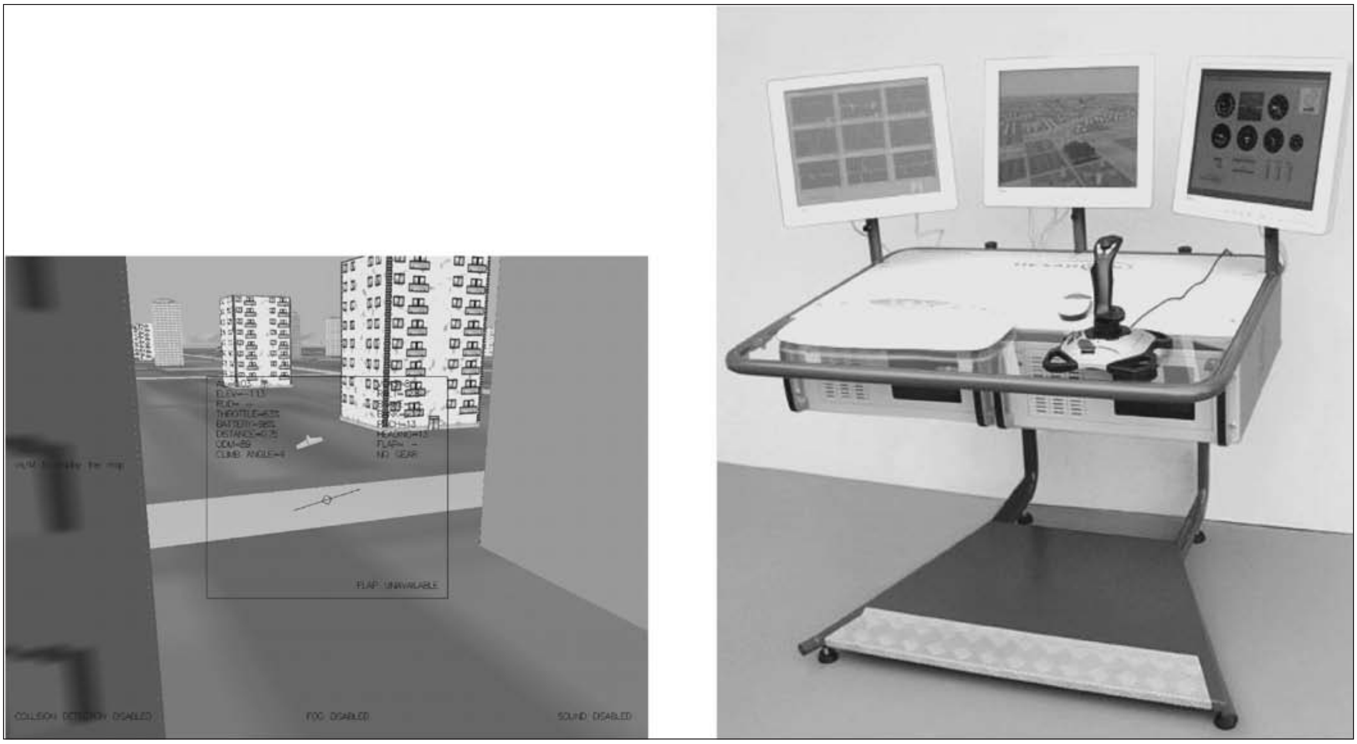
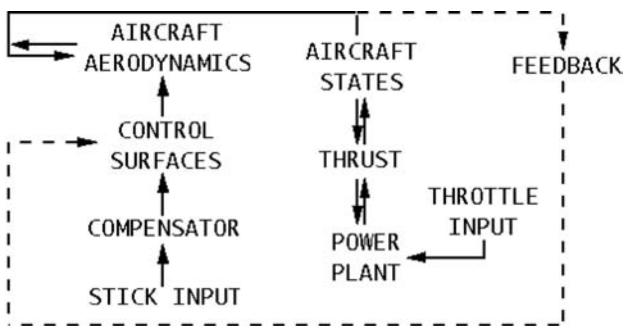


Figure 2 The mathematical model implemented in the simulator



that for the current analysis is reduced to the following proportional form:

$$\Delta\delta_e(s) = k_u \cdot u(s) + k_w \cdot w(s) + k_q \cdot q(s) + k_\theta \cdot \theta(s)$$

The gains of the feedback loop (k_u, k_w, k_q, k_θ) and the parameters of the lead compensator (T_1, T_2) were determined with a search strategy based on a GA.

Design procedure

The genetic solver adopted for the design of the control system (i.e. to obtain the feedback matrices) is a Fortran version of the driver described by Carroll (1996a, b). The code initializes a random sample of individuals with different parameters to be optimized using the GA approach. The selection scheme used is tournament selection with a shuffling technique for choosing random pairs for mating. The routine includes binary coding for the individuals, jump mutation, creep mutation, and the option for single-point or uniform crossover. Niching, elitism and an option for the number of children per pair of parents are available. Finally, the solution using a micro GA is also possible. This last switch significantly reduced the number of function evaluations and demonstrated faster convergence to the near-optimal region (Carroll, 1996a, b). Note that average population fitness values are not meaningful with a micro-GA because of the start-restart nature of the micro-GA evolution process.

Many numerical experiments were performed in Carroll (1996a, b) in order to tune the search algorithm adopted and, as a result, the suggested set-up is extended for the present application. The micro-GA operating mode was adopted combined with uniform crossover (the probability for a crossover occurring at each chromosome position was fixed to 0.5). The code was set for a maximum micro population size of ten individuals, 72 bits per individual and six parameters (i.e. 12 binary bits per parameter and 2^{12} possible solutions per parameter). Niching and elitism were activated, creep mutation was disabled and two children per pair of parents were considered.

The fitness function to be optimized is supplied by means of an external subroutine called by the solver. In this case, a fitness function was designed in order to meet the handling qualities requirements for the longitudinal plane.

A complete analysis of aircraft handling qualities criteria is presented in Mitchell *et al.* (2004), Anonymous (1997, 1980) and Moorhouse and Woodcock (1982). The attention is here focused on the small amplitude short term criteria which relate to the aircraft's ability to perform small amplitude tasks such as closed loop compensatory tracking. The requirements are given in terms of bandwidth ω_{BW} and phase delay τ_{P} which are obtained from the frequency response (Bode plot) of the attitude response to pilot input, that is expected to match a reference level for gain margin and phase margin. The bandwidth parameter is a measure of the maximum closed loop frequency that the pilot can achieve with gain control without compromising the stability of the system. Phase delay $\tau_{\mathrm{P}} = \Delta\phi_{2\omega 180}/2\omega_{180}$ is a measure of how quickly the phase lag increases beyond the neutral stability point ω_{180}. Aircraft with large phase delays are prone to plot induced oscillations, i.e. small changes in pilot gain result in large loss of phase margin. A key aspect of bandwidth criteria is that they do not assume a characteristic response shape. Furthermore, no lower order model based on approximations was considered as a reference for the design of the requirements in Anonymous (1997). Therefore, they are applicable to any response type (conventional, rate command attitude hold or attitude command attitude hold).

The handling qualities requirements and the frequency response shaping specifications are implemented in the fitness function used by the genetic search algorithm as parameters x_{k}: the bandwidth ω_{BW}, the phase delay τ_{P}, the average low frequency amplitude A_{low} of the frequency response, the peak gain value A_{max} and the average gain over the bandwidth A_{avg}. Hence, for the present analysis the number of parameters is $n = 5$.

The fitness function selected (Fantinutto *et al.*, 2005) for the optimal search is a n-dimensional function (elliptic paraboloid) defined over the search space. The function is maximized when the distance from the desired value $x_{\mathrm{k_R}}$ for the parameters x_{k} (given as an input of the search process) is minimized. The shaping of the fitness functions is obtained by selecting the axis range for each single parameter x_{k}, i.e. by defining an adequate performance of the fitness function in the symmetric interval $[x_{\mathrm{k_L}}, x_{\mathrm{k_U}}]$ where the maximum is found for $x_{\mathrm{k_R}} = (x_{\mathrm{k_L}} + x_{\mathrm{k_U}})/2$. The peak values of the function are scaled to obtain the same maxima in the center of the acceptable range of variation for each parameter x_{k}.

A deficiency function is also optionally added to the fitness function computed for the parameters x_{k} to include the effect of system stability in terms of penalty for the individuals which exhibit undamped poles. This solution does not interfere with the search process as the pole placement required to design the controlled system is not influenced within the area delimited by an acceptable damping ratio.

The GA iterates generation after generation the gains of the control system in order to fit the frequency response to the parameters x_{k} specified by the user. Convergence is verified by tracking the performance (i.e. the fitness function) for the best individual of each generation.

Analysis of the results

The aircraft configuration selected for this study is representative of the so-called MicroHawk300 version of the above mentioned fixed wing micro aerial vehicle (Plate 1), with an approximate weight of 100 g and a wingspan of 337 mm.

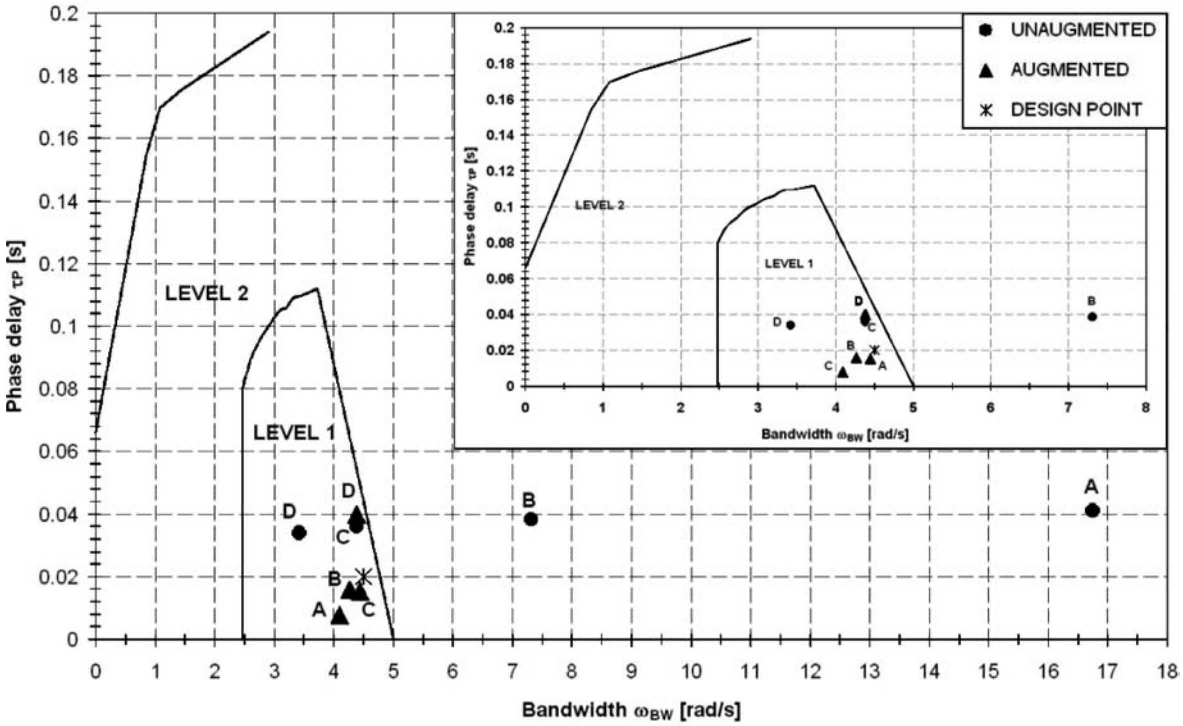
The control design procedure was extended to different flight regimes in terms of airspeed V in order to reproduce an overview of the flight envelope for the vehicle. The estimation of parameters is focused on pitch attitude frequency response to longitudinal stick input given by the pilot (Figure 3). The unaugmented platform is gain limited and exhibits Level 2 short term longitudinal handling qualities in case of low speed flight ($V < 15$ m/s) which makes remote piloting still possible with some workload for the pilot, in particular when visual perception of flight is obtained from onboard video camera only. As a concern, low speed flight is mandatory for ground observation and to increase flight endurance. As an additional remark, it should observed that differently from the typical control design case, for the present application, a reduction in terms of bandwidth is required for the augmented vehicle to fly in the Level 1 boundaries. The design point for search process was fixed at bandwidth $\omega_{\mathrm{BW}} = 4.5$ rd/s with a phase delay $\tau_{\mathrm{P}} = 20$ ms. The augmented aircraft shows enhanced handling qualities (always phase limited), in particular for the low speed flight regime, as both bandwidth and delay fall in the Level 1 contour area. The solutions were attracted by the design point with a minimum spread which is the consequence of the mixed nature of design requirements including shaping of frequency response given by the parameters A_{low}, A_{max} and A_{avg}.

The convergence of the search algorithm was always successful as the fitness function at the end of the process approached 99 percent of the absolute maximum. The search procedure was initially extended to 10,000 generations and the performance of the best individual was tracked step after step (Figure 4). In any case, the initial increase of the fitness function is quite sharp even if a second phase of slow convergence is observed up to 3,000 generations. After this second phase, no substantial increase of performance for the best individual was found. Note that due to the limited number of individuals for each generation typical of micro-GA algorithms, the evolution process is completed quite rapidly on a personal computer after some tuning of the search space dimension.

The Bode plot of the frequency response is obviously altered for the augmented aircraft in accordance with the design requirements (Figure 5) as low frequency gain is increased, the peak gain is smoothed and the slope of the phase is constant in the frequency range for bandwidth and delay estimation, without any abrupt drop in phase lag.

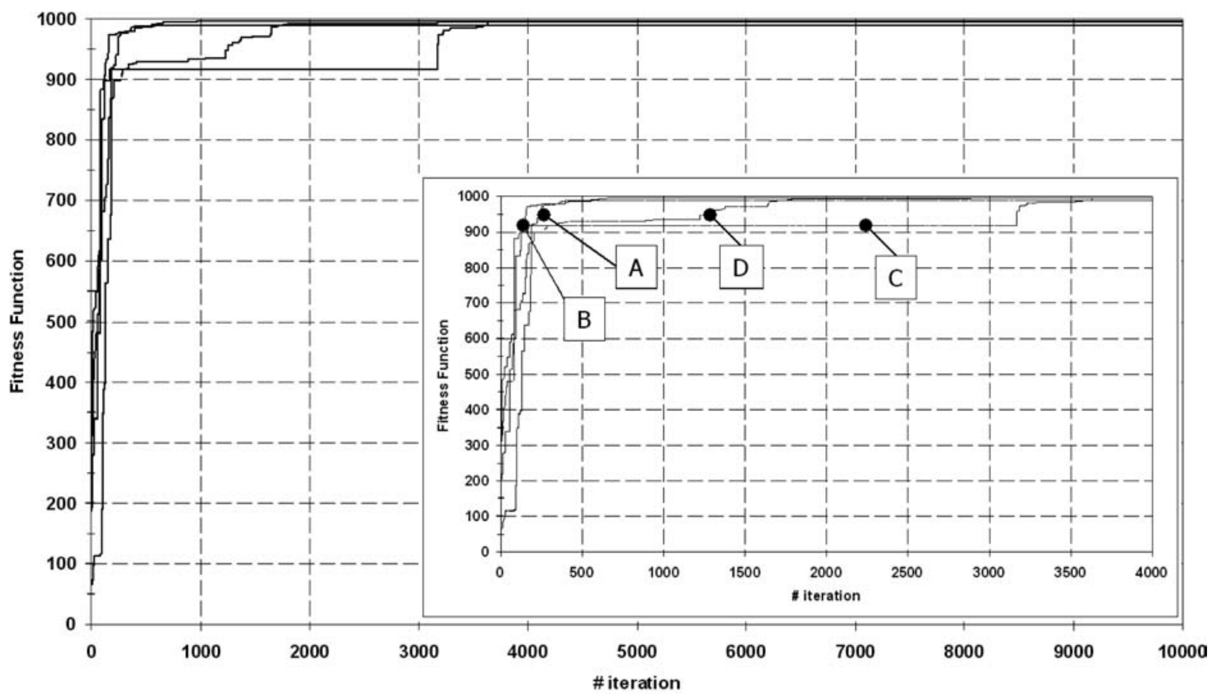
The time domain attitude response to small stick inputs reflects the beneficial influence of the control system (Figure 6) as overshoots and oscillations are reduced without any large perturbation of the flight path induced by

Figure 3 The handling qualities levels before and after the inclusion of the control system



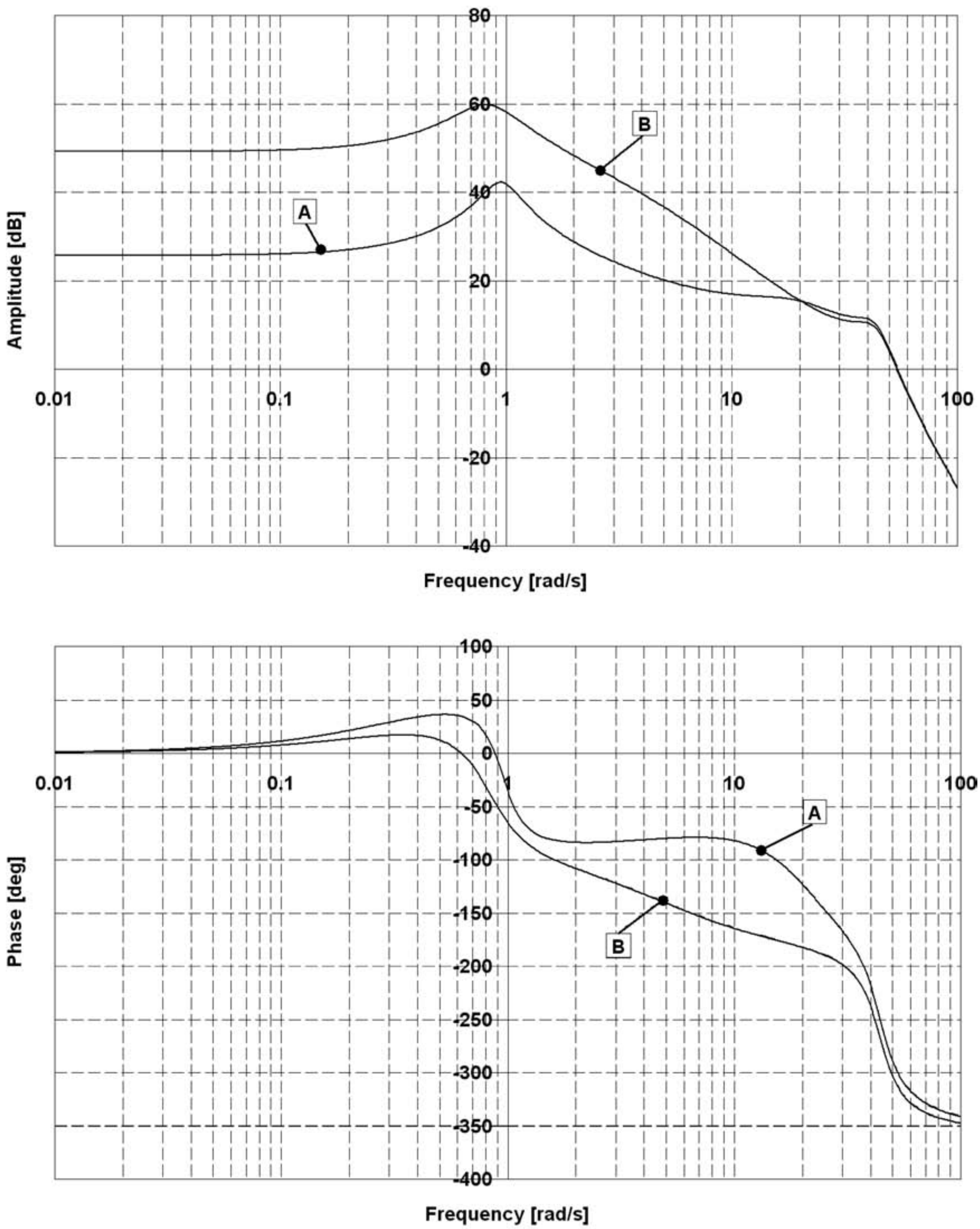
Note: A: V = 10 m/s – B: V = 12.5 m/s – C: V = 15 m/s – D: V = 17.5 m/s

Figure 4 The search process and the performance in terms of evolution



Note: A: V = 10 m/s – B: V = 12.5 m/s – C: V = 15 m/s – D: V = 17.5 m/s

Figure 5 The frequency domain response before and after the inclusion of the control system

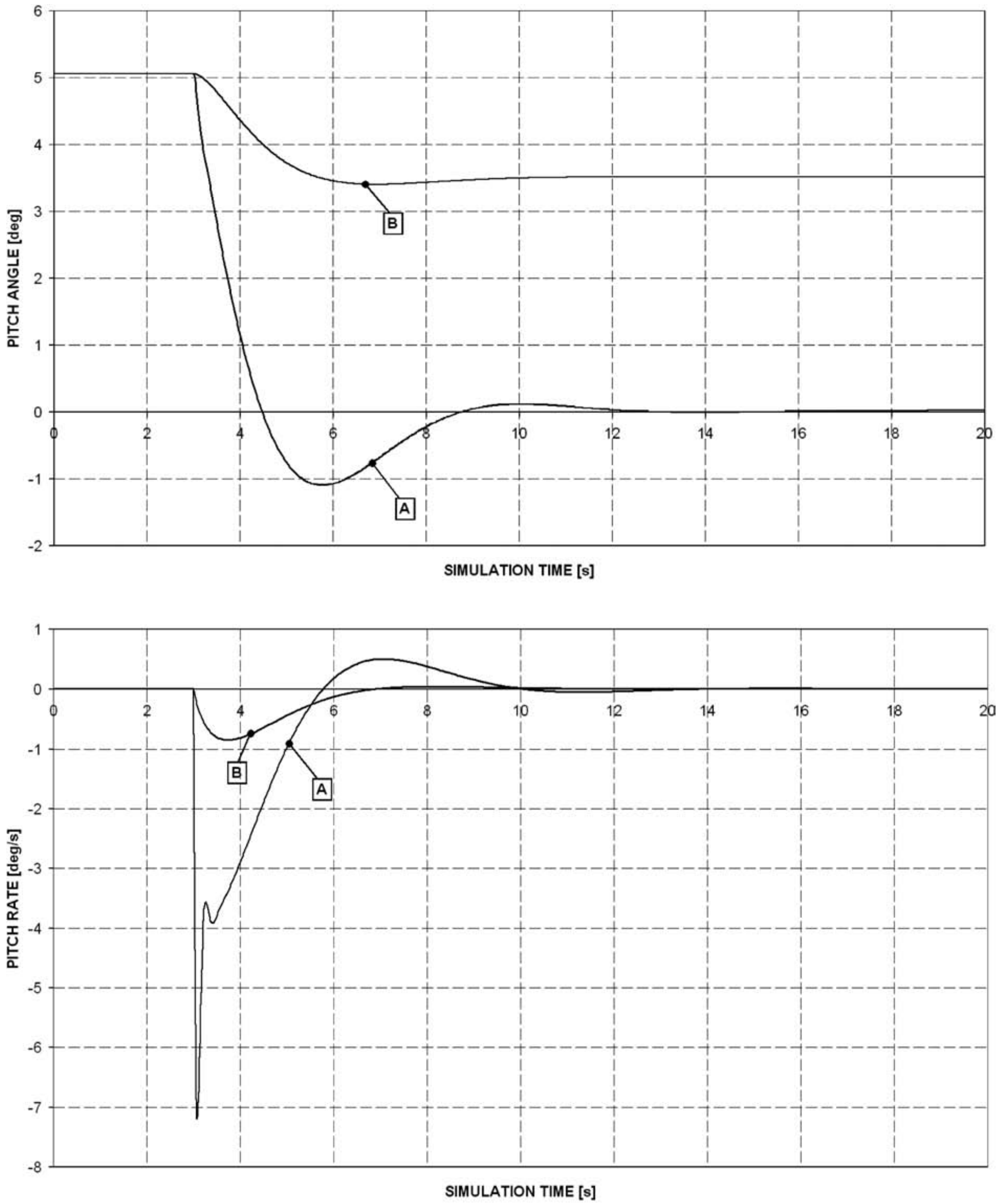


Note: V = 12.5 m/s – A: unaugmented – B: augmented

significant changes for airspeed or angle of attack (Figure 7). As a matter of fact, an exponential filter combined with a rate limiter was required for radio control inputs to minimize the sensitivity to small amplitude stick commands during precision tracking flight tests for the unaugmented aircraft.

Finally, the scheduled gain matrix obtained with the search process was implemented in the simulator in order to reproduce the augmented piloted response. As a qualitative result, the flight control system was found to be effective in reducing pilot workload during simulated flight tasks which reproduced accurate trajectory tracking remote piloting with onboard vision. Future work is expected to produce in-flight experiments with an augmented vehicle that should confirm the promising performances obtained in the virtual environment.

Figure 6 The time domain response before and after the inclusion of the control system



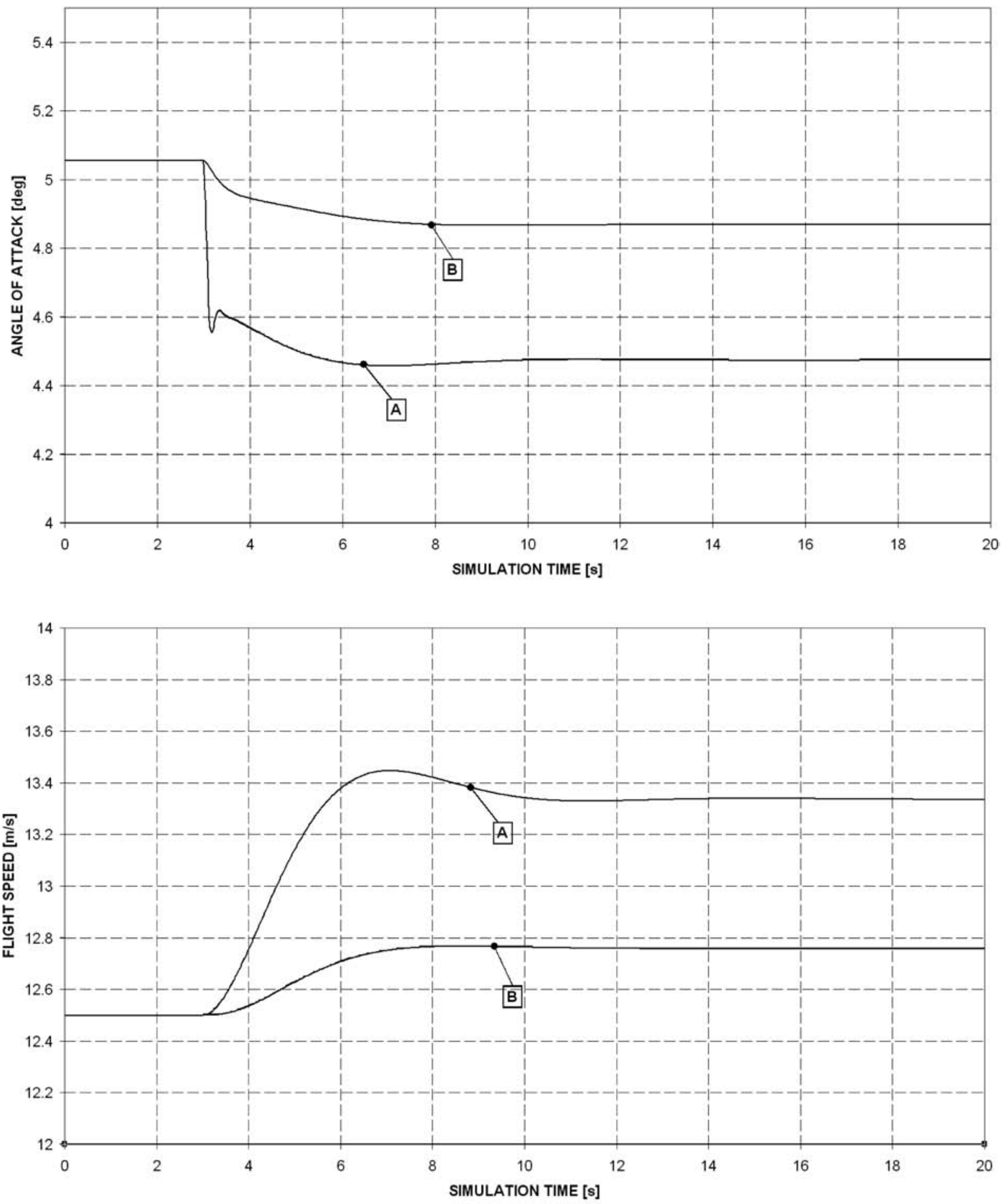
Note: V = 12.5 m/s – $\Delta\delta_e$ = 0.1° – A: unaugmented – B: augmented

Concluding remarks

The results show that an optimal search process based on a GA can implement the handling qualities requirements with a computational procedure that is straightforward.

The algorithm is robust in terms of search and the evolution is completed with a limited computational workload. The nonlinearity of the mathematical model seems not to provide limitations within the level of complexity here considered.

Figure 7 The time domain response before and after the inclusion of the control system



Note: $V = 12.5$ m/s – $\Delta\delta_e = 0.1°$ – A: unaugmented – B: augmented

The requisites for bandwidth and delay implemented in the search process make pole location and system stability transparent to the designer. In any case, stability of the solution is ensured with deficiency functions which penalize the evolution of unstable individuals. The parameters are general in use as no specific aircraft response type is taken as a reference for the estimation of handling qualities requirements. Future experimental work will provide insight for the definition of specific Level 1 boundaries for micro aerial vehicles in remotely piloted flight.

The virtual environment is useful to test remote piloting with unconventional onboard visual cues. Accurate attitude tracking can be tested in a safe environment with complete flight data streaming and real time visualization. This is important in applications in which technical and dimensional limitations may preclude complete real time data link during flight tests in the first development phase of the vehicle.

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