Multi-Rate Path-Following Control for Unmanned Air Vehicles

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Abstract: A methodology is provided to tackle the path-following integrated guidance and control problem for unmanned air vehicles with measured outputs available at different rates. The path-following problem is addressed by defining a suitable non-linear path dependent error space to express the vehicle’s nonlinear dynamics. The main novelty of the method is to explicitly take into account the different temporal characteristics of the onboard sensor suite in the controller design and implementation. The proposed controller solution relies on a linear parameter varying structure that naturally exploits these multi-rate characteristics of the system outputs to obtain the desired properties for the resulting integrated guidance and control system. Due to the periodic time-varying characteristics of the multi-rate mechanism, the controller synthesis is dealt with under the scope of linear periodic systems theory. The effectiveness of the path-following methodology is accessed in simulation for low altitude terrain-following maneuvers of a small-scale helicopter using a full dynamic model of the vehicle.

Keywords: Guidance and Control, Path Following, Multi-rate Systems, Periodic Systems, Linear Parameter Varying Systems

1. INTRODUCTION

This paper presents a path following control solution for unmanned air vehicles (UAVs) that naturally takes into account the multi-rate characteristics of the onboard sensor suite. This feature is of paramount importance in UAVs applications where the linear position measurements are typically available at a lower rate than that of the remaining variables, as is the case when using the Global Positioning System (GPS).

In the field of motion control for autonomous vehicles, path-following has proven to be an efficient alternative to trajectory tracking. While in the trajectory tracking problem the vehicle is expected to follow a reference defined in terms of space and time-coordinates, in the path-following problem the vehicle is required to converge and to follow a path without temporal restrictions. In this way, path-following approaches usually exhibit enhanced performance when compared to trajectory tracking (Aguiar and Hespanha (2007)), with smoother convergence to the path and less demand on the control effort. In Cunha and Silvestre (2005) a solution was presented for the path-following problem for unmanned air vehicles that relies on the definition of an error space to accurately model the vehicle’s nonlinear equations. By taking into account both the kinematics and dynamics this approach provides an integrated guidance and control solution to the problem of motion control for UAVs.

Multi-rate control theory has received considerable attention in the last few decades (see, for example Colaneri and Nicolao (1995), Lall and Dullerud (2001) and the references therein). If we assume that the sensor sampling and actuators updating rates are related by rational numbers, a multi-rate system can be modeled as a periodic system (Lall and Dullerud (2001)). In autonomous vehicles applications the multi-rate nature of the sensor suite can either be taken into account in the navigation system (Vasconcelos et al. (2004)) or directly in the controller. This last approach is followed in Antunes et al. (2007) where a methodology is proposed for the control of multi-rate nonlinear systems using gain-scheduling control, that eliminates the need to feedforward the values of the state variables and inputs at trimming. Gain-scheduling control is a powerful technique extensively used in aerospace applications that exploits the advantages of linear systems controller design to synthesize a nonlinear compensator, which typically has a linear parameter varying (LPV) structure (Rugh and Shamma (2000)).

In this paper the path-following problem is addressed by defining a suitable non-linear path dependent error space to express the vehicle’s nonlinear dynamics (see Cunha and Silvestre (2005)). The proposed controller design methodology relies on a linear parameter varying structure with integral action that takes into account the multi-rate characteristics of the sensors and actuators. Based on this structure a gain-scheduling controller design and implementation procedure is followed (Rugh and Shamma (2000)), where the multi-rate linear controller

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synthesis problem is addressed within the scope of the $H_2$ control theory for linear discrete time periodic systems.

The proposed technique is applied to the design of a multirate integrated guidance and control system for a small-scale helicopter, which is evaluated in simulation for a low altitude terrain following maneuver. The reference path considered is composed by the concatenation of straight lines and results from applying a terrain reconstruction technique to Laser Range Scanner measurements (Paulino et al. 2006).

The remainder of the paper is organized as follows. We briefly introduce the helicopter model in Section 2. The path-following problem formulation is presented in Section 3 and the controller design methodology for nonlinear multirate system is described in Section 4. Section 5 focuses on the controller design and implementation procedure. Finally, simulation results are presented in Section 6 and the concluding remarks in Section 7.

The notation is fairly standard. The space of $n$-dimensional continuous-time signals, $x(t) : \mathbb{R}^+ \rightarrow \mathbb{R}^n$, will be denoted by $L(\mathbb{R}^+ \times \mathbb{R}^n)$ or simply by $L(\mathbb{R}^n)$ and the space of $n$-dimensional discrete-time signals, $x_k : Z^+ \rightarrow \mathbb{R}^n$, will be denoted by $l(Z^+ \times \mathbb{R}^n)$ or simply by $l(Z^+)$.

The notation $\text{diag}([a_1 \ a_2 \ldots \ a_n])$ indicates a block diagonal matrix where the entries $a_i$ can be either scalars or matrices. Whenever the matrices dimensions are clear, identity and zero matrices are denoted by $I$ and $0$. Otherwise the dimensions are explicit indicated as in $I_3$, $\theta_{3 \times 2}$. A vector of $n$ ones is denoted by $1_n = [1 \ 1 \ldots 1]^T$. Further notation will be introduced when necessary.

2. HELICOPTER DYNAMIC MODEL

This section summarizes the helicopter dynamic model. For a comprehensive coverage the reader is referred to Cunha and Silvestre (2003) and Cunha (2002) where a full nonlinear dynamic model of a small-scale helicopter is derived from first principles.

Let $(\lambda_0, \lambda_1, \lambda_c, \lambda_0) \in SE(3) := \mathbb{R}^3 \times SO(3)$ denote the configuration of the body frame attached to the vehicle’s center of mass \( \{B\} \) with respect to the inertial frame \( \{I\} \), where \( \lambda_0 R = R_c(\psi_c) R_t(\theta_c) R_v(\phi_c) \) is a rotation matrix parameterized by the Z-Y-X Euler angles \( \lambda_c = [\phi_c \ \theta_c \ \psi_c]^T \), \( \lambda_0 \in [-\pi/2, \pi/2], \phi_c, \psi_c \in \mathbb{R} \). In addition, let $v = [u_n \ v_n \ w_n]^T$ and $\omega = [p_n \ q_n \ r_n]^T$, denote the linear and angular body velocities, respectively, where $v = p R^T \dot{p}_n$, $\omega = p R^T \omega_n$, and $\omega_n$ is the angular velocity of \( \{B\} \) with respect to \( \{I\} \). The helicopter dynamics can then be derived by using the conventional six degree of freedom rigid body equations of motion

\[
\begin{cases}
\dot{v} = f(v, \omega, u) + p R [0 \ 0 \ 0]^T \\
\dot{\omega} = n(v, \omega, u) \\
\dot{\lambda}_0 = \lambda_0 R v \\
\dot{\lambda}_c = Q(\phi_c, \theta_c) \omega
\end{cases}
\]

The actuation $u = [\theta_0 \ \theta_1 \ \theta_c \ \lambda_0]$ comprises the main rotor collective input $\theta_0$, the main rotor cyclic inputs, $\theta_1$, and the tail rotor collective input $\lambda_0$. The force and moment vectors can be decomposed as $f = f_{mr} + f_{tr} + f_{fs} + f_{tp} + f_{fn}$ and $n = n_{mr} + n_{tr} + n_{fs} + n_{tp} + n_{fn}$, respectively, where the subscripts $mr$, $tr$, $fs$, $tp$ and $fn$ stand for main rotor, tail rotor, fuselage, horizontal tail plane and vertical tail, respectively. The simulation model includes the rigid body, main rotor flapping, and Bell-Hiller stabilizing bar dynamics, which are not presented here for the sake brevity but can be found in Cunha and Silvestre (2003).

3. PATH-FOLLOWING FORMULATION

The integrated guidance and control strategy proposed in Cunha and Silvestre (2005) for the path-following problem, consists in defining a path-dependent transformation, which is applied to the vehicle’s dynamic and kinematic model to express it in a convenient error space. The problem of steering the unmanned vehicle along a predefined path with a given velocity profile, is then reduced to that of regulating the error variables to zero. In order to present this transformation, we first introduce the frames \( \{T\} \) and \( \{C\} \), depicted in Fig. 1, and a collection of references associated to these frames. These elements can be briefly described as follows (see Cunha and Silvestre (2005) for further details and derivations):

Frame \( \{T\} \)

There is an almost exact correspondence between \( \{T\} \) and the standard Serret-Frenet frame. The $x$ axis, $x_T$, is aligned with the tangent vector to the path, so that the linear velocity reference in this frame is given by

\[ v_T = V_r \begin{bmatrix} 1 & 0 \end{bmatrix}^T \]

where $V_r$ is the desired linear speed. The angular velocity reference, also expressed in \( \{T\} \), can be written as

\[ \omega_T = V_r \begin{bmatrix} \tau & 0 & \kappa \end{bmatrix}^T \]

where $\tau$ is the torsion and $\kappa$ the curvature, which characterize each point on the path. The frame \( \{T\} \) moves along the path attached to the point on the path closest to the vehicle, meaning that the position error can be defined as the two-dimensional vector $d_t = [d_y \ d_z]^T \in \mathbb{R}^2$ that satisfies

\[ \begin{bmatrix} 0 \\ d_t \end{bmatrix} = \tau R (\hat{p}_n - \hat{p}_T), \]

where $\hat{p}_T$ is the position of \( \{T\} \) with respect to \( \{I\} \). It is also useful to consider the Z-Y-X Euler angles $\lambda_T = [\phi_T \ \theta_T \ \psi_T]^T$, which describe the orientation of \( \{T\} \), and the linear speed $V_T$, which is related to the vehicle’s velocity by

\[ V_T = \frac{1}{1 - \kappa d_y} \begin{bmatrix} 1 & 0 \end{bmatrix}^T \tau R v. \]

Frame \( \{C\} \)

The need to define \( \{C\} \) arises from the fact that while following a path, the vehicle may take different orientations or even rotate with respect to the path. The reference of orientation for the vehicle is given by the Z-Y-X Euler angles $\lambda_C = [\phi_C \ \theta_C \ \psi_C]^T$, $\theta_C \in [-\pi/2, \pi/2]$, $\phi_C, \psi_C \in \mathbb{R}$. The angular velocity of \( \{C\} \) with respect to \( \{T\} \) expressed in \( \{T\} \) is denoted by $\omega_C$. The origin of \( \{C\} \) coincides with that of \( \{T\} \).

Given the definitions of \( \{T\} \) and \( \{C\} \), the error state vector $x_e \in \mathbb{R}^{11}$ can be defined as
It is well known that for a vehicle with dynamics described by (1), the set of trimming trajectories comprises all $x$-aligned helices ($\kappa = 0$, $\alpha = 0$, $\gamma = 0$) and $\lambda_T = \text{sign}(\kappa)\sqrt{\kappa^2 + \tau^2} \cdot [0 \ 0 \ 1]^T$, followed at constant speed ($V_T = 0$) and constant orientation with respect to the path ($\tau, \omega_c = 0$) (Silvestre et al. (2002)). Consider the following variables: the linear speed reference $V_r$, the flight path angle $\theta_r$, the yaw orientation of the vehicle with respect to the path $\psi_{st} = \psi_c - \psi_t$ and the yaw rate $\dot{\psi}_r = V_r \sqrt{\kappa^2 + \tau^2}$. As discussed in Cunha and Silvestre (2005), for the case of helicopters this set of variables

$$\xi = (V_r, \psi_r, \theta_r, \psi_{st})$$

adequately parameterizes the vehicle’s equilibrium points corresponding to trimming paths. The error dynamics defined with respect to these operating points can be written as

$$P(\xi) := \begin{cases} \dot{x}_e = f_e(x_e, u, \xi), \\ y_e = h_e(x_e, \xi), \end{cases}$$

and is such that $f_e(0, u_\xi, \xi) = 0$ and $h_e(0, \xi) = 0$. The output $y_e$ is chosen in such a way that at steady state the condition $y_e = 0$ implies $x_e = 0$, therefore characterizing an equilibrium point. It can be shown that the output given by

$$y_e = \begin{bmatrix} v_e + \frac{\nu R}{\psi_e} & 0 \\ \psi_e & d_t \end{bmatrix} \in \mathbb{R}^4$$

verifies this condition. By applying integral action to (5), we can guarantee that $y_e$ (and consequently $x_e$) goes to zero at steady-state.

Recalling that $\xi$ is a constant parameter vector, the linearization of $P(\xi)$ about $(x_e = 0, u = u_\xi)$ results in a time-invariant family of linear systems of the form

$$P_l(\xi) = \begin{cases} \dot{x}_e = A_l(\xi)x_e + B_l(\xi)u_s, \\ y_e = C_l(\xi)x_e, \end{cases}$$

where $u_s = u - u_\xi$, $A_l(\xi) = \frac{\partial f_c}{\partial x_e}(0, u_\xi, \xi)$, $B_l(\xi) = \frac{\partial f_c}{\partial u}(0, u_\xi, \xi)$, and $C_l(\xi) = \frac{\partial h_c}{\partial x_e}(0, \xi)$.

4. NONLINEAR MULTI-RATE CONTROLLER DESIGN

In this section we summarize the gain-scheduling methodology for nonlinear multi-rate systems presented in Antunes et al. (2007), which will be applied to the multi-rate path-following control problem.

4.1 Problem Setup

Consider the nonlinear system

$$G := \begin{cases} \dot{x}(t) = f(x(t), u(t), w(t)) \\ y(t) = h(x(t), w(t)) \end{cases}$$

where $x(t) \in \mathbb{R}^n$ is the state, $u(t) \in \mathbb{R}^m$ is the control input, and the vector $w(t) \in \mathbb{R}^{n_w}$ contains references $r(t)$ and possibly other exogenous inputs. The vector $y(t) \in \mathbb{R}^p$ can be decomposed as $y(t) = [y_m(t)^T \ y_r(t)^T]^T = [y_m(x(t), w(t))^T \ h_r(x(t), w(t))^T]^T$ where $y_m(t) \in \mathbb{R}^{n_{y_m}}$ is a vector of measured outputs available for feedback and $y_r(t) \in \mathbb{R}^{n_{y_r}}$ is a vector of tracking outputs, which we assume to have the same dimensions as the control input, $n_{y_r} = m$. This vector is required to track the reference $r(t)$ with zero steady-state error, i.e. the error vector defined as $e(t) := y_r(t) - r(t)$ must satisfy $e(t) = 0$ at steady-state. Some of the components of $y_r(t)$ may be included in $y_m(t)$ as well.

Linearization family

We assume that there exists a unique family of equilibrium points for $G$ of the form

$$\Sigma := \{(x_0, u_0, w_0): f(x_0, u_0, w_0) = 0, y_{e_0} = h_r(x_0, w_0) = r_0\}$$

which can be parameterized by a vector $\alpha_0 \in \Xi \subset \mathbb{R}^s$, such that

$$\Sigma = \{(x_0, u_0, w_0) = a(\alpha_0), \alpha_0 \in \Xi\}$$

where $a$ is a continuously differentiable function. We further assume that there exists a continuously differentiable function $v$ such that $\alpha_0 = v(y_0, w_0)$. Applying the function $v$ to the measured values of $y$ and $w$, we obtain the variable $\alpha = v(y, w)$, which is usually referred to as the scheduling variable.

Linearizing the system $G$ about the equilibrium manifold $\Sigma$ parameterized by $\alpha_0$ yields the family of linear systems

$$G_l(\alpha_0) := \begin{bmatrix} \dot{x}_l(t) \\ y_{l_1}(t) \\ y_{l_2}(t) \end{bmatrix} = \begin{bmatrix} A_l(\alpha_0) & B_l(\alpha_0) & 0 \\ C_l(\alpha_0) & D_l(\alpha_0) & 0 \\ 0 & w_l(t) & w_{l_2}(t) \end{bmatrix} \begin{bmatrix} x_l(t) \\ w_l(t) \\ u_{l_2}(t) \end{bmatrix}$$

where, e.g. $A_l(\alpha_0) = \frac{\partial f_l}{\partial x}(\alpha(\alpha_0))$ and $x_l(t) = x(t) - \alpha_0$. 

Fig. 1. Coordinate frames: inertial $\{I\}$, body $\{B\}$, tangent $\{T\}$, and desired body frame $\{C\}$
Multi-rate sensors and actuators

We consider that the sample and hold devices that interface the discrete-time controller and the continuous-time plant operate at different rates. The actuators updating and sensor sampling times do not have to be equally spaced but the periodicities of the updating and sampling mechanisms are assumed to be rationally related. Let \( t_s \) denote the greatest common divisor of these periods and consider a set of \( h \)-periodic matrices \( \Gamma_k = \Gamma_{k+h} \), \( \Omega_k = \Omega_{k+h} \) taking the form: 
\[
\Gamma_k = \text{diag}(g_1(k), \ldots, g_{nk}(k)),
\]
where \( g_i(k) = 1 \) if output \( i \) is sampled at time \( t_k = kt_s \) and \( g_i(k) = 0 \) otherwise; \( \Omega_k := \text{diag}(\alpha_1(k), \ldots, \alpha_{nk}(k)) \), where \( \alpha_j(k) = 1 \) if input \( j \) is updated at time \( t_k = kt_s \) and \( \alpha_j(k) = 0 \) otherwise. Then the multi-rate input and output mechanisms, denoted by \( S_{mr} \) and \( H_{mr} \), respectively, can be modeled as:
\[
S_{mr}: \mathcal{L}(\mathbb{R}^+) \mapsto \mathcal{L}(\mathbb{Z}^+)
\]
\[
y_k = \begin{bmatrix} y_{mk} \\ y_{rk} \end{bmatrix} = \begin{bmatrix} \Gamma_{mk} & 0 \\ 0 & \Gamma_{rk} \end{bmatrix} \begin{bmatrix} y_{mk}(t_k) \\ y_{rk}(t_k) \end{bmatrix} = \Gamma_k y(t_k)
\]
\[
H_{mr}: \mathcal{L}(\mathbb{Z}^+) \mapsto \mathcal{L}(\mathbb{R}^+)
\]
\[
\xi_{k+1} = (I - \Omega_k)\xi_k + \Omega_k u_k, \quad \xi_0 = 0
\]
\[
u_k = (I - \alpha_k)\xi_k + \alpha_k u_k
\]
\[
u(t) = \bar{u}_k \quad t \in [t_k, t_{k+1}]
\]
We also introduce the error variable \( e_k = y_{rk} - r_k \), where \( r_k = \Gamma_{rk} r(t_k) \).

4.2 Multi-rate controller design and implementation

Consider the linearized system (10) with multi-rate interface (11) which can be written as the series connection \( S_{mr}G_tH_{mr} \). Suppose that given a fixed \( \alpha_0 \) we design a linear controller for this multi-rate system that takes the form depicted in Fig. 2. In the figure \( C_I \) and \( C_D \) correspond to discrete time linear periodic integrators and differentiators, respectively, that can be written as:
\[
C_I = \begin{bmatrix} x_{k+1}^I = x_k^I + \Omega_k u_k \\ y_k^I = x_k^I + \Omega_k h_k \end{bmatrix}
\]
\[
C_D = \begin{bmatrix} x_{k+1}^D = (I - \Gamma_{mk})x_k^D + \Gamma_{mk}y_k^I \\ y_k^D = -\Gamma_{mk}x_k^D + \Gamma_{mk}u_k^D \end{bmatrix}
\]
These two systems are introduced in such a way that the controller \( C_K \) operates in a differential manner, that is, it takes in the plant’s output differential values and provides differential values to be integrated into the actuation signals. The importance of this structure for gain-scheduling control will be clarified shortly.

Consider the system \( G_a \) shown in Fig. 2, which is given by the series connection of \( C_I, S_{mr}G_tH_{mr} \) and \( C_D \), i.e. \( G_a = C_D S_{mr}G_tH_{mr}C_I \). As proved in Antunes et al. (2007), this augmented system \( G_a \) preserves the detectability and stabilizability properties of the original system \( G_t \), under mild assumptions. Hence, there exists a stabilizing controller \( C_K \), which is in general periodically time-varying. Furthermore, due to integral action and given that \( C_K \) stabilizes the closed-loop system, the structure achieves zero steady-state error for \( y \). Suppose the equations for \( C_K \) are given by:
\[
C_K(\alpha_0) = \begin{bmatrix} x_{k+1}^K \\ y_{k+1}^K \end{bmatrix} = \begin{bmatrix} A^K_{\alpha_0}(\alpha_0) & B^K_{\alpha_0}(\alpha_0) & B^K_{\alpha_0}(\alpha_0) \\ C^K_{\alpha_0}(\alpha_0) & D^K_{\alpha_0}(\alpha_0) & D^K_{\alpha_0}(\alpha_0) \end{bmatrix} \begin{bmatrix} x_k^K \\ y_k \end{bmatrix}
\]
and that we have designed a parameter-dependent family of controllers of the form \( \tilde{C}_K C_K(\alpha_0) C_{D} \).

Consider then the following implementation for the non-linear gain-scheduled controller, taking the form of a linear parameter varying (LPV) controller and obtained by replacing the time-frozen parameter \( \alpha_0 \) with the scheduling variable \( \alpha_k \).

\[
K = \begin{bmatrix} x_{k+1}^K \\ y_{k+1}^K \end{bmatrix} = \begin{bmatrix} I - \Gamma_{mk} \Gamma_{mk} \\ I - \Gamma_{mk} \Gamma_{mk} \end{bmatrix} \begin{bmatrix} x_k^K \\ y_k^K \end{bmatrix}
\]

(14.A)

The scheduling variable \( \alpha_k \) is computed on-line from the plant outputs and exogenous variables. The system described by (14.A) is used to perform a hold operation on the output \( y_k \) so that the scheduling variable \( \alpha_k \) is computed, at each iteration, according to the last sampled value of the output. The exogenous vector is assumed to be available at each sampling instant, so that \( w_k = w(t_k) \).

Since the proposed controller operates in a differential manner, we can show that it verifies the following the linearization property: At each equilibrium point parameterized by \( \alpha_0 \), the gain-scheduled controller \( K \) linearizes to the designed controller \( C_I C_K(\alpha_0) C_D \). See Rugh and Shamma (2000) for the importance of such property and for examples of incorrect implementations where this property is not verified. The controller structure is inspired in the velocity implementation (Kaminer et al. (1995)) - a technique devised to guarantee that the referred linearization property holds for continuous gain-scheduled controllers, which also operates in a differential manner.

5. MULTI-RATE CONTROLLER DESIGN AND IMPLEMENTATION

We assume that the state variables of the vehicle (1) are all available at a rate of 50 Hz except for the components of the linear position, which are assumed to be updated at the lower rate of 2.5 Hz. The actuation update rate is also set to 50 Hz, therefore yielding \( h = 20 \) and \( t_s = 0.02 \).

In accordance with Section 4.1 and assuming that the
nonlinear plant is given by (4), we consider the error output $y_e = y_e$ and define the measured output $y_m = x_e$. The set of matrices $Ω_k$ and $Γ_k$ are determined by

$$\Omega_k = I_4, \quad Γ_{mk} = \begin{cases} I_{11} & k = 0 \\ \text{diag}(13, 13, 02, 13) & \text{otherwise} \end{cases}, \quad Γ_{vk} = \begin{cases} I_4 & k = 0 \\ \text{diag}(03, 1) & \text{otherwise} \end{cases}, \quad k = 0, \ldots, h - 1. \quad (15)$$

Making use of the controller structure presented in Section 4, a family of linear controllers is designed for the parameterized family of models described by (6) with the multi-rate characteristics just described, using a standard method of gain-scheduling theory. This method comprises the following steps: i) obtain a finite set of parameter values from the discretization of the continuous parameter space, ii) synthesize a linear controller for each linear plant (6), obtained from the linearization of the nonlinear plant for each value of the scheduling parameter, iii) interpolate the coefficients of the linear controllers to obtain a continuously parameter-varying controller. We detail each of these steps in the remainder of this section.

5.1 Discretization of the parameter space

The set of parameters that characterize a trimming path, which corresponds to an equilibrium point for the vehicle’s dynamic equation, is given by (3). In this paper, we restrict the set of trimming trajectories considered for terrain-following maneuvers to straight-lines ($\psi_r = 0$), with constant linear speed $V_r$ and vehicle’s yaw angle aligned with the path ($\psi_{ct} = 0$). The parameter space is then reduced to $\alpha_0 = \theta_r$. Moreover if we assume that $\phi_B = 0$ and $\theta_B = 0$ at trimming and consider the variable

$$\alpha = \arctan(-\frac{w_B}{u_B})$$

we can show that at equilibrium $\alpha = \alpha_0$ (Paulino et al. (2006)), and therefore $\alpha$ conforms with the general description of scheduling variable given in Section 4.1.

The finite set of values for this parameter, $\{\bar{\alpha}_0\}$, was chosen to be

$$\bar{\alpha}_0 = [-50 -40 -30 -20 -10 0 10 20 30 40 50] \frac{\pi}{180} \text{rad}$$

which means that the conditions under which the vehicle is expected to operate include following straight lines in trimmed flight, with a flight path angle ranging between -50 and 50 degrees.

5.2 Linear controller synthesis

For linear controller synthesis, the standard LQG solution for periodic systems presented in detail in Colaneri and Nicolao (1995) was used to synthesize a controller $C_K(\alpha_0)$ for each parameter value $\alpha_0$. The augmented system $G_a = CDG(CI)$ seen by the controller is obtained from (6) and (15). Notice that $G_a$ has $n_y + n_y = 11 + 4 = 15$ outputs and $n_m + n_y = 11 + 4 + 11 = 26$ state variables, which determine the dimensions of $C_K$. The weights defining the LQG problem were adjusted to yield good transient error responses and smooth actuation for the closed-loop system.

5.3 Interpolation

The resulting finite set of synthesized controller coefficients, for example $\{A^B_2(\alpha_0)\}$, were interpolated using least squares yielding a continuously parameter dependent controller $C_IC_K(\alpha_0)C_D$, where the describing matrices are quadratically parameter dependent, for example

$$A^B_2(\alpha_0) = A^{k_1}_2 + \alpha_0 A^{k_2}_2 + \alpha_0^2 A^{k_3}_2,$$

$$B^k_{1h}(\alpha_0) = B^{k_1}_{1h} + \alpha_0 B^{k_2}_{1h} + \alpha_0^2 B^{k_3}_{1h}.$$  

The disadvantage of this technique is that there is no guarantee that, even for fixed parameter values, the controller obtained by interpolation stabilizes the closed loop system. This analysis was made a posteriori, verifying that for a dense grid of fixed values of $\alpha_0$ the closed loop system is stable.

Having designed the continuously parameter varying controller $C_I C_K(\alpha_0) C_D$, the final gain-scheduled controller $K$ takes the form (14), which, as noted earlier, eliminates the need to feedforward the trimming values for the state variables and inputs. Another interesting feature of the methodology is that the implementation of anti-windup schemes is straightforward due to the fact that integral action is provided at the plant’s input.

6. RESULTS

The simulation results presented in this section were obtained using the non-linear dynamic model SimModHeli, parameterized for the Vario X-Treme model-scale helicopter (Cunha and Silvestre (2003)). The helicopter is required to perform a low altitude terrain-following task, by describing the path shown in Figure (3) with constant linear speed $V_r = 1.5 \text{ m/s}$. The reference path may result from a terrain following reconstruction algorithm (see Paulino et al. (2006)) and is divided in the four following segments: i) a level flight segment along the $x$ axis, ii) a climbing ramp with a flight path angle of $\theta_r = 0.5236$ rad, iii) a level flight segment along the $x$ axis, and finally iv) a descending ramp with a flight path angle of $\theta_r = -0.2618$ rad. Figure (4) shows the time evolution of the errors $v_e = [v_e, v_w, v_o]^T$, $\omega_{e} = [\omega_e, \omega_w, \omega_o]^T$, $dt$, and $\lambda_e = [\theta_e, \phi_e, \psi_e]^T$, actuation, and multi-rate velocity and position signals. From the figure, we can conclude that the helicopter with the gain-scheduling multi-rate controller efficiently performs the desired task. Notice that after each transition, the helicopter quickly converges to the reference path corresponding to zero-steady state errors. Furthermore the actuation is kept within the limits of operation, exhibiting a smooth behavior.

![Fig. 3. Helicopter performing a low altitude terrain-following maneuver.](image-url)
7. CONCLUSIONS

In this paper, the path-following problem for unmanned air vehicles was tackled using an integrated guidance and
control approach. The solution consists in formulating the problem based on an adequate error space, where path-following reduces to driving this error to zero. To this end, a gain-scheduling control methodology was provided that takes into account the multi-rate characteristics of the measured outputs. Simulation results showed good performance of the resulting multi-rate integrated guidance and control system in a low altitude terrain following task, when the linear position is available at a rate lower than of the remaining variables.

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Fig. 4. Time evolution of the error state variables, actuation, and velocity and position measurements.