Lateral Stability Augmentation System for Micro Air Vehicle - Towards Autonomous Flight

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Abstract—This paper presents a generic design methodology of robust fixed order H₂ controller and onboard computer for Micro air Vehicles. The efficacy of the proposed method is demonstrated by designing a fixed order robust H₂ stability augmentation system for lateral dynamics of a Micro air Vehicle, named Sarika-1. Strengthened Discrete Optimal Projection Equations, which approximate the first order necessary optimality condition, are used for the controller design. Effect of low frequency gust disturbance and high frequency sensor noise is alleviated through the output sensitivity and control sensitivity minimization. Digital Signal Processor (DSP) based onboard computer named Flight Instrumentation Controller (FIC) is designed to operate under automatic or manual mode. The controller is ported on to the flight computer, and subsequently, it is validated through the real-time hardware-in-loop-simulation. The responses obtained from the hardware-in-loop-simulation compare well with those obtained from the off-line simulation.

Key words—MAV, DSP, SDOPE, FIC, HILS, Fixed order controller, Robust controller

I. INTRODUCTION

Recently, the desire for low cost, portable, low-altitude aerial surveillance has driven the development and testing of smaller and smaller aircrafts, known as Micro Air Vehicles (MAVs)[1-2]. MAVs have a wide range of applications both in commercial and military applications. Payloads ranging from cameras to acoustics to weapons, MAVs allow for a variety applications within the three dimensional freedom of the sky. MAVs are remotely controlled by radio control system and are difficult to fly due to its unconventional design and sometimes due to unpredictable flight characteristics. Another limitation of radio controlled aircraft is the range of the pilot’s sight. Hence, to alleviate the necessity of an expert pilot and to operate the MAV in a wide variety of missions, a robust optimal flight controller that provides an acceptable stability and performance over the entire flight envelope, is a must. Hence, design and realization of the robust performance controller to achieve the complete autonomy of a MAV is an active field of the research [3].

In the last three decades, the quest for robust controllers resulted in a widespread search for controllers, which robustly stabilize the system [4, 5]. Abundant literature is available on the design of robust controller using H₂ [6, 7] methods and μ Synthesis [8, 9]. However, H₂ controller is the result of worst-case design technique; hence such methods lean too heavily on stability robustness and sacrifice an adequate view of performance. Very often, stable and smooth flight of a MAV is essential for surveillance and aerial survey missions. H₂ performance level is an indicator of real life performance of a robust controller [10, 11]. However, a significant shortcoming in [10, 11] is that these techniques generally lead to higher order controllers. However, Stability of the reduced-order controller and that of the closed-loop system cannot be guaranteed, and optimality may also be lost [12]. Very little effort is directed towards the design and development of a fixed low-order robust H₂ controller, particularly for the MAVs. Robust performance is a major concern for the proper functioning of the MAVs. This paper extends [13] and documents the design and evaluation of a robust fixed-order H₂ controller for a discretized lateral dynamics of Sarika-1.

In references [14, 15], an optimal steady state fixed-order dynamic compensator is obtained from the solution of four matrix equations coupled through a projection operator, whose rank is precisely equal to the order of the compensator. In reference [15], four matrix equations known as strengthened discrete optimal projection equations (SDOPEs) are used to design a reduced-order LQG compensator in time domain. The weighting matrices for state and control variables are constant. In contrast, selection of frequency dependent weights enables the designer to shape the responses tighter in pre-specified frequency ranges by giving them larger weights, clearly at the expense of larger errors at other frequency ranges that are of lesser importance. Therefore, in this paper, the SDOPEs [15] are used to design robust fixed-order H₂ controller with the frequency dependent weights. The design allows the required trade-off between sensitivity and control sensitivity of the closed-loop system. The main contribution of this paper is the design and real-time validation of a single controller, which meets the flying qualities, disturbance rejection and noise attenuation specifications for the entire flight envelope (flight speeds ranging from 15 m/s to 26 m/s) of Sarika-1. The controller is validated by means of offline simulation and real-time hardware-in-loop simulation (HILS) experimental setup.

The organization of this paper is as follows. Section 2 gives the model description and modeling of Sarika-1 for its lateral dynamics. Section 3 gives the controller design specifications and principles of fixed order robust H₂ controller. The results and analysis of offline simulation and real time HILS experiment using
the designed controller is given in section 4. Finally, conclusions are drawn in section 5.

II. MAV DESCRIPTION AND ITS MODELLING

A. MAV Description

MAV named Sarika-1 is shown in Fig. 1, which is a remotely piloted small flying vehicle of about 1.28 m span and 0.8 m length and weights around 1.75 kg at takeoff. It has a rectangular wing of planform area of 0.2688 m² and a constant area square section fuselage of width 0.06 m. The control surfaces are elevators, ailerons and rudder. The power plant is a 4 cc propeller engine (OSMAX -25LA), which uses methanol plus castor oil as fuel, with 10 to 15 % nitro-methane to boost the engine power. Sarika-1 has a provision to carry video camera and sensor payloads.

Fig. Sarika 1 Micro Air Vehicle

B. Lateral Dynamics of Sarika1

Linearized state space model representing small perturbation lateral dynamics are developed for a straight and level flight at an assumed constant altitude of 100 m above ground level at Bangalore (or 1000 m above the sea level) trimmed at five operating points in the speed range of 15 - 25 m/s. Linearized state space equations, (state variables are side slip angle, β, roll rate, p, yaw rate, r, and bank angle, φ) in its matrix form can be represented as follows[16-17]:

\[
\begin{bmatrix}
\beta \\
p \\
r \\
φ \\
\end{bmatrix}
= \begin{bmatrix}
\frac{\gamma}{U_c} \\
\frac{\gamma}{U_c} \\
\frac{\gamma}{U_c} \\
\frac{\gamma}{U_c} \\
\end{bmatrix}
+ \begin{bmatrix}
\frac{\gamma}{U_c} \\
\frac{\gamma}{U_c} \\
\frac{\gamma}{U_c} \\
\frac{\gamma}{U_c} \\
\end{bmatrix}
\begin{bmatrix}
\frac{\gamma}{U_c} \\
\frac{\gamma}{U_c} \\
\frac{\gamma}{U_c} \\
\frac{\gamma}{U_c} \\
\end{bmatrix}
\begin{bmatrix}
\beta \\
p \\
r \\
φ \\
\end{bmatrix}
\]

The measured variables are lateral acceleration, ay, roll rate, p and yaw rate, r of the vehicle and are represented in matrix form as follows:

\[
Y = \begin{bmatrix}
Y_y \\
Y_r \\
Y - U_c \\
0 \\
0 \\
1 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
\end{bmatrix}
\begin{bmatrix}
\beta \\
p \\
r \\
φ \\
\end{bmatrix}
\begin{bmatrix}
Y_y \\
Y_r \\
Y - U_c \\
0 \\
0 \\
1 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
\end{bmatrix}
\begin{bmatrix}
\beta \\
p \\
r \\
φ \\
\end{bmatrix}
\]

The dynamic derivatives are calculated using analytical approach [18], while static and control derivatives are calculated based on the wind tunnel generated data [19]. One of the controller design requirement is to design a single controller at the central operating point of the vehicle and using for all flight conditions. Hence, for the controller design purpose, a flight speed of 18m/s is selected. At 18 m/s flight speed, the state space representation of the lateral dynamics of Sarika-1 is given by,

\[
\begin{bmatrix}
\beta \\
p \\
r \\
φ \\
\end{bmatrix} = \begin{bmatrix}
-0.9972 \\
374.7358 \\
18.4827 \\
0 \\
\end{bmatrix}
\begin{bmatrix}
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
\end{bmatrix}
\beta
\]

Similarly, the mathematical models are developed at other operating points, i.e. at 15 m/s, 20 m/s, 22 m/s and 25 m/s. for the further analysis.

Frequency and damping ratios of lateral dynamics at five different operating points in the flyable speed range of 15-25 m/s shows a very poor dutch roll damping at all flight conditions and hence smooth flight of Sarika-1 is difficult without closed loop augmentation system. Since, Sarika-1 does not have sensors to measure true or indicated airspeed and it uses non-inertial quality sensors; gain/controller scheduling is not feasible. Hence the objective of this research is to design and develop a single controller at its central operating point, so as to use the same for the entire flight envelope.

To perform augmented control, information must be known about the current state of the aircraft, as well as the pilot inputs from the transmitter. The state data is obtained from two on-board sensors, a rate gyro and accelerometer. These sensors are directly interfaced to the on-board flight system, the FIC, the design of which is explained below.

C. On Board flight system, FIC

The selection of the onboard computer is based on many constraints. Size, speed of computation, available space, power, and allowable weight are few among them. Keeping these constraints in mind, the flight instrumentation controller (FIC) in Fig. 2 is designed around two TI based DSPs viz., TMS320LF2407 and TMS320VC33. TMS320LF2407 DSP is used for data
acquisition and motor control application while TMS320VC33 DSP is used for mathematical computations and data memory management. Communication between the two DSPs is through inbuilt synchronous serial channel operating at 5MBPS. Owing to the complexity involved, simple errors in the software development can often lead to critical failures that result in crashes and loss of MAV airframe. To mitigate this problem, hardware digital switching logic is provided so that the pilot can switch-over from automatic to manual mode at will (so that command signals received from the ground bypasses the controller block, and directly get linked the actuator servo) and can safely land the aircraft. Manual mode of flight is also useful for the estimation of the aircraft flight parameters since some of these parameters get camouflaged on closing the feedback loop.

III. DESIGN SPECIFICATIONS AND PRINCIPLES OF H₂ CONTROLLER

A. Design Specifications

The closed-loop design specifications for the lateral dynamics are determined from its expected responses to pilot/ command inputs sent from the aileron and rudder joystick. Thus, the main requirement of stability augmentation system (SAS) towards the improvement of handling qualities summarized as in S1

S1. Level 1 flying quality requirements

Dutch roll damping ratio ≥ 0.5
Roll subsidence time constant < 1 s
Spiral mode-minimum time to double the amplitude > 12 s
For Sarika-1 airframe dynamics, only dutch roll damping is poor, leading to large settling time. Hence, dutch roll damping needs to be improved. The specifications for the spiral mode and roll modes are satisfied. However, these properties should not be deteriorated when the loop is closed.

S2. Disturbance rejection Specification

Disturbance rejection specification is: Minimize the sensitivity function below 0 dB when ω < 10 rad/s.

S3. Sensor noise attenuation Specification

Obtain: - 40 dB/decade roll off above ω = 15 rad/s

S4. Robustness Specification

The controller should be robust to structured and unstructured uncertainty in plant models at all flight conditions

Apart from the above specifications, the closed loop system should also be robust to maximum expected time delays, which may arise due to computational complexity. In addition, the control surface deflection should not exceed its full-scale deflection of +16 degrees.

To meet the above closed loop requirements, fixed order robust H₂ controller is designed by considering the performance objective of minimization of H₂ norm of the closed loop transfer function Tzw given by:

\[ \min \| T_{zw} \| = \min \| W_1(z)S_0(z) \| W_2(z)S(z)K(z) \| \]  \hspace{1cm} (5)

where, w is the Tzw, is the transfer function between the performance outputs i.e output sensitivity S₀ \((S₀ = (I + GKK)^{-1})\) and control sensitivity SK (with \(S = (I + KK′G)^{-1}\)) functions to the disturbance input. Also K represents the controller transfer function. W₁ and W₂ are the weighting matrices used to minimize sensitivity and control sensitivity at low frequency and high frequency specified in the design specifications. Reduced fixed order controller is designed by solving strengthened discrete optimal projection equations.[15]

IV. RESULTS AND ANALYSIS

Suitable weighing matrices are selected by trial and error method and minimum order controller is designed to meet the design specifications. It is found that a third order controller is sufficient to meet the closed loop requirements. The two elements of transfer function matrix of the third order controller K₁w₂ is given by,

\[
K(z) = \frac{1}{\Delta(z)} \begin{bmatrix} 0.18z(z-0.37)(z-0.99) & 0.76(z-0.66)(z-0.97) & 0.069(z^2 - 1.61z + 1.03) \\
0.0015(z^2 - 0.25z + 0.035) & 0.057(z + 0.04)(z-0.0634) & -0.001(z^2 + 0.68z + 0.64) 
\end{bmatrix}
\]  \hspace{1cm} (6)

where, \(\Delta(z) = (z - 0.9)(z^2 + 0.267z + 0.48)\).

With this controller it is found that the closed loop dutch roll damping increases above 0.5 at all flight conditions, hence, the stringent level-one flying quality requirement is met.

A. Time Response Study

Closed loop time responses are simulated with a pulse input of amplitude 0.1ms applied for duration of 2s. The closed loop pulse responses of the lateral variables at different flight condition are shown in Figs 3 – Fig.5.
The responses are fast and well damped, demonstrating the improvements over its plant responses. With controller, the settling time of the variables, r, p, and \( \phi \) reduces to 3 seconds from 8 s at 15 -18 m/s and at higher speed it remains at 5 s. The peak amplitude of the closed loop responses of \( \beta \) and \( \phi \) are reduced slightly compared to its plant response.

### B. Controller Implementation and Validation

The control law is coded on to the onboard computer, FIC, using floating-point programming. Since the inputs to the controller are in volts and the output needs to be in-terms of milliseconds of PWM signal, a relation between the voltage to PWM signal width is found experimentally as:

\[
PWM = (V_{\text{signal}} - V_{\text{offset}}) \times 1.18 \text{ ms.}
\]  

A computer-supervised scheduler enables the controller inputs and driving scenarios, in a time indexed manner. To record the controller’s response to the given time indexed stimuli, data is logged from both the simulator and controller with the integrated data.
acquisition system. Extensive closed loop test is conducted at different flight conditions in order to validate the controller in real time.

The HILS experiment is done for lateral dynamics of Sariak-1, the results of which are shown in Figs 6 - 8 (corresponding to a flight speed of 18 m/s). These signals are captured in real time for a short interval of time of 20s. The aileron command input, shown in Fig. 6, is given from the RF Transmitter. At first a negative going pulse of 0.03 ms (with respect to the neutral value of 0.08 ms) PWM signal is applied at \( t = 1.5 \) s and held it there for about 2 s. This input is then followed by another positive going pulse, also of amplitude 0.03 ms (with respect to the neutral value) starting at \( t = 3.5 \) s. Then the input is brought back to the neutral position at \( t = 9.5 \) s and there after held constant at the neutral position continuously.

Feedback signals used for the controller design are \( a_y \), roll rate, \( p \) and yaw rate \( r \) of the vehicle. These signals are generated in real time using dSPACE 1104 RTI/RTW and are shown in Fig. 7. The lateral acceleration changes between -0.2 m/s\(^2\) to 0.2 m/s\(^2\) (with respect to 0.4 m/s\(^2\)) when the input varies between -0.03 ms to 0.03 ms above its neutral value of 0.08 ms. These values are comparable with those obtained from offline simulations. Similarly, the roll rate, \( p \) varies between 5 degrees/s to -10 degrees/s and is matching well with the offline results. The closed loop responses of the state variables (\( \beta \) and \( \phi \)) are also simulated in real time and are shown in Fig. 8. One can see that the responses are well damped with fast settling time and almost match with its desktop simulation.

The experiment is again repeated for other flight speeds (15 m/s and 25 m/s) and the responses were found to be satisfactory. Thus, HILS results of lateral dynamics validated the controller for its actual flight.
CONCLUSIONS

A new approach on design of discrete robust frequency shaped $H_2$ optimal flight stabilization system for micro air vehicle named Sarika-1 is developed. The design technique uses Strengthened Discrete Optimal Projection Equations. Detailed time and frequency domain analysis shows that the $H_2$ optimal controller is able to meet all design specifications. A single controller robustly stabilizes Sarika-1 with margins better than a minimum requirement of 6 dB gain margin and 60 deg phase margin at all flight conditions within the speed range of 15 to 25 m/s. Off-line time responses demonstrates that flight stabilization performs well up to the designer’s expectation. Subsequently, real time validation of the controller, which is implemented on the digital signal processor based onboard computer substantiates the offline simulation results. The real time HILS responses math well with those of the desktop simulation responses. Thus, robust $H_2$ stability augmentation system can be successfully used towards equipping the Micro air Vehicles with autonomous capabilities that could significantly enhance the utility of the Micro air Vehicles for a wide range of missions.

REFERENCES