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DECENTRALIZED FLIGHT CONTROL INTEGRATION AND PERFORMANCE EVALUATION

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Abstract

Decentralized flight control shows great advantage in implementation, and is well fitted into a systematic flight control systems development and engineering process. However, the preservation of locally achieved design specifications under the integrated system environment is largely unknown. This work proposes two control integration approaches to address this challenge. It describes both open-loop and closed-loop integration strategies within an integrated control framework. Furthermore, the selection of candidate subsystems is also taken into account during integration. Using an integrated longitudinal pitch attitude and speed control example, the performance of both strategies is evaluated. Numerical simulation results are included for further demonstration.

Key Words

Decentralized control, control integration, performance analysis

1. Introduction

Modern flight control systems become more and more complicated in structure. They often contain multiple subsystems or channels to address the complexity of the target tasks. Such a hierarchical structure presents increasing challenges to the control engineers and demands a systematic design process. The flight control system development process normally involves progressing cycles of requirement analysis, system partitioning, controller design, integration, testing, and performance verification [1]. It is widely acknowledged that controller design itself is no longer an independent task. A successful controller will be designed to meet the immediate specifications at the local component level. After integrating the component into the system, the controller will maintain those specifications, and achieve overall performance requirements. This article addresses the first design challenge, that is, how to preserve local design specifications during system integration.

There are generally two design approaches for control integration. The *centralized approach* is based on an integrated system description, taking advantage of its explicit considerations of all the possible interactions between subsystems [2, 3]. The drawback, however, is that practical implementation is not always possible, or even advisable for a number of reasons [4]. Contrary to the centralized approach, the *decentralized approach* follows a given hierarchical architecture. Under this approach, the system is broken down into various (possibly interacting) subsystems. Each subsystem's required dynamic characteristics are defined or derived based on overall system performance requirements. Then, separate controllers can address these different subsystem specifications [5]. However, this approach will leave the integration and testing process in an ad hoc manner, especially when the complexity of a control system increases. The interacting effects (especially the negative effects) among subsystems can no longer be ignored as they may cause significant deterioration in overall performance.

Here, we address the *decentralized control integration from a performance perspective*, that is, we will investigate different control integration approaches and evaluate their design effectiveness based on how they contribute to achieving performance requirements. The purpose of this exploration is twofold: to draw some conclusions by comparing various integration strategies, and to provide a practical guideline for selecting control integration approaches. In order to illustrate our point, we apply our theoretical investigation to a flight control example with pitch attitude and speed control subsystems.

2. Integrated Pitch Attitude and Speed Control

Modern aircraft include a variety of automatic control systems that aid the flight in navigation and flight management and augment the stability characteristics of the airplane [6]. A linearized longitudinal flight equations of motion is represented by the following transfer matrix [7]:

$$\begin{bmatrix} u \\ w \\ q \\ \theta \end{bmatrix} = \begin{bmatrix} G_{ue} & G_{up} \\ G_{we} & G_{wp} \\ G_{qe} & G_{qp} \\ G_{\theta e} & G_{\theta p} \end{bmatrix} \begin{bmatrix} \delta_e \\ \delta_p \end{bmatrix} \tag{1}$$

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where $u, w, q, \theta, \delta_e, \delta_p$ represent the forward speed, vertical speed, pitch rate, pitch angle, elevator input, and throttle (propulsion) input, respectively. We also use the convention of transfer function, for example, $G_{\theta e}$ represents the transfer function from the elevator δ_e to the pitch angle output θ.

In this work, we look at two autopilot control channels, the pitch attitude control and the speed control. The pitch attitude control is a flight control system that keeps pitch attitude through control of the elevator. The speed control is also an automatic flight control system that maintains a constant speed or Mach number through coordinated control of the throttle and the elevator.

2.1 Pitch Attitude Control

In a pitch attitude control channel, the pitch angle is sensed by a vertical gyro and compared with the desired pitch angle to create a displacement of the elevator so that the error signals are reduced. Because the phugoid oscillation can occur if the pitch angle θ is allowed to change, a pitch attitude hold feature in the autopilot would be expected to suppress the phugoid. Such a pitch attitude hold system is illustrated in Fig. 1.

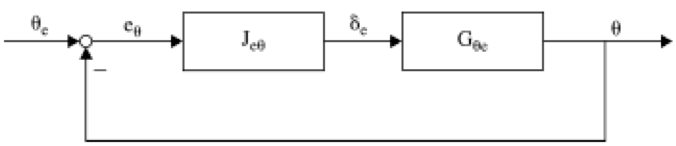

Figure 1. Pitch attitude control.

It is clear that the closed-loop transfer function from command θ_c to output θ is given by $L_{\theta\theta} = G_{\theta e} J_{e\theta} / (1 + G_{\theta e} J_{e\theta})$, where $J_{e\theta}$ is the locally designed controller. Further, we assume the design specifications in this channel are formulated as:

$$\begin{cases} \phi_{pitch:overshoot} \leq \alpha_1 \\ \phi_{pitch:sse} \leq \alpha_2 \end{cases} \tag{2}$$

where overshoot and steady-state error (sse) specifications represent the unit-step input (in this case, δ_e) responses, and α_1, α_2 are design tolerances (desired specification values).

2.2 Speed Control

In speed control, however, we see that both elevator and throttle influence the speed, but that the short- and long-term effects of each of these controls are quite different. The throttle channel (Fig. 2(a)) primarily affects the speed in the short term only. For a change of steady-state speed, the elevator channel must also be used, as shown in Fig. 2(b).

The throttle $\delta_p \to u$ channel has the following closed-loop transfer function from command u_c to output u, with the controller denoted by J_{pu}: $L^p_{uu} = G_{up} J_{pu} / (1 + G_{up} J_{pu})$. The elevator $\delta_e \to u$ channel has the following closed-loop transfer function from command u_c to output u, with the controller denoted by J_{eu}: $L^e_{uu} = G_{ue} J_{eu} / (1 + G_{ue} J_{eu})$. Assume the similar overshoot and sse specifications at the local $\delta_p \to u$ or $\delta_e \to u$ channels:

$$\begin{cases} \phi_{speed:overshoot:p} \leq \beta_1 \\ \phi_{speed:sse:p} \leq \beta_2 \end{cases} \quad \text{or} \quad \begin{cases} \phi_{speed:overshoot:e} \leq \gamma_1 \\ \phi_{speed:sse:e} \leq \gamma_2 \end{cases} \tag{3}$$

2.3 Integration Architecture

To simplify our discussion, we assume an integrated pitch and speed control system consisting of only two automatic control channels, the pitch control and the speed control channels. Clearly, a sophisticated speed control system might use both the throttle and elevator channels. To demonstrate different control integration strategies, we further assume that either the throttle $\delta_p \to u$ channel or the elevator $\delta_e \to u$ channel must be chosen to establish the final integration structure. Therefore, the integrated pitch/speed control system will have the choice of Fig. 3(a) or 3(b), depending on the selection of speed control channel.

Note that the selection may be easily made through aerodynamic analysis, that is, we can analyze physical impacts of these two speed control channels on aerodynamic parameters, such as speed u and pitch angle θ, at the phugoid mode and the short-period modes. Instead, this work focuses on the decision-making strategy purely from the control and integration perspective, under the assumption that no such aerodynamic behaviour is analytically known or given.

Clearly, the presented integration architecture still maintains a decentralized structure. Then the question becomes: how to design local controllers $K_{e\theta}, K_{eu}$, or K_{pu} to keep their respective design specifications (2) and (3),

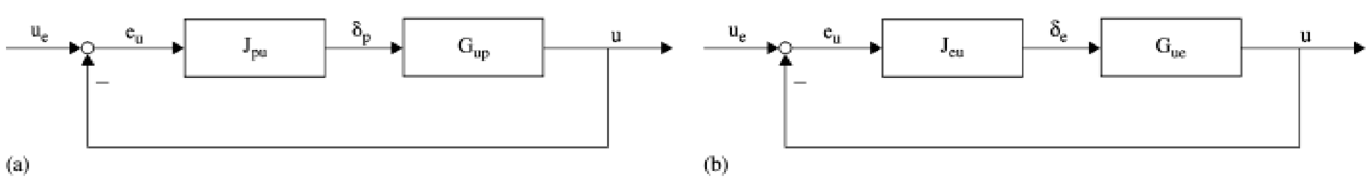

Figure 2. Speed control channel.

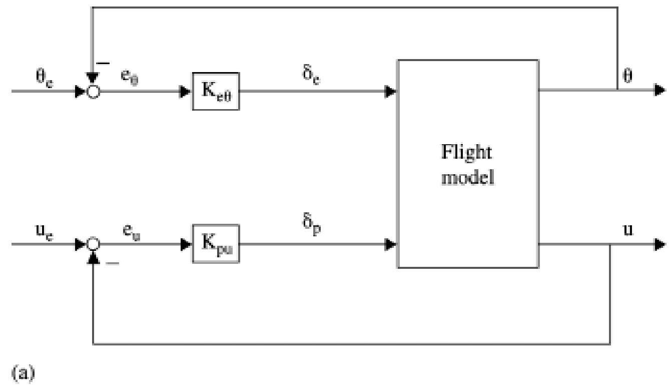

Figure 3. Integrated pitch/speed control.

under the integrated control framework? Before the main results are presented in the next sections, we will give a numerical example for illustration purposes.

2.4 Numerical Example

We choose the numerical example of a Boeing 747 transport cruising in a horizontal flight at 40,000 feet and Mach number 0.8 [7]. Furthermore, we assume that three "perfect" local PID controls have already been designed to satisfy their respective specifications. These controllers are also chosen from [7]. The local channel simulation results are shown in Figs. 5(a), 5(b), and 5(c), respectively. Once we have achieved the local design, we will investigate the decentralized controller design and integration as shown in Fig. 3. Note that the controller $K_{e\theta}, K_{eu}$, or K_{pu} may or may not be the same as the local design $J_{e\theta}, J_{eu}$, or J_{pu}.

Remark: One major point here is that the local control channel design is a relatively easy task, when the designer only needs to focus on the single input-output specifications. Many control techniques, both classical and modern, can be applied here for each channel design. We choose the PID control structure as an example, assuming one can tune the PID gains to satisfy the local design specifications. There are other approaches to deal with multi-objective control requirements, including the author's work in multiple simultaneous specification (MSS) design [8, 9]. Therefore, the focus here is the investigation of control integration strategy, rather than local MSS control design.

3. Integrated Control Framework and Problem Statement

As mentioned in Section 2, the success in the integrated pitch/speed control system development depends on a proper selection of the control and integration architecture (a decision-making strategy to choose Fig. 3(a) or 3(b)), and the satisfaction of local design specifications under this integrated system. In this paper, we start with establishing a generic integrated system, as shown in Fig. 4.

The overall control system framework contains a generic (including both centralized and decentralized) controller structure:

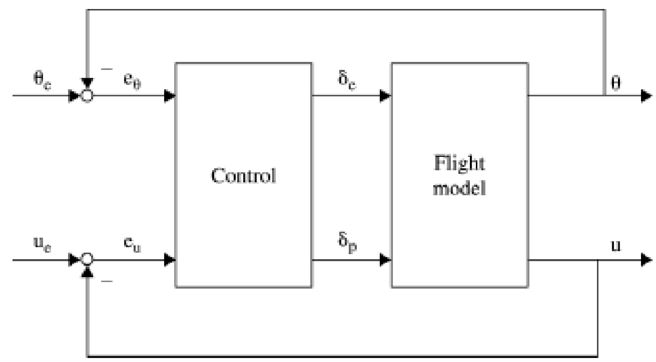

Figure 4. Integrated pitch/speed control system framework.

$$\begin{bmatrix} u \\ \theta \\ \cdots \\ e_u \\ e_\theta \end{bmatrix} = \begin{bmatrix} 0 & 0 & \vdots & G_{ue} & G_{up} \\ 0 & 0 & \vdots & G_{\theta e} & G_{\theta p} \\ \cdots & \cdots & \vdots & \cdots & \cdots \\ 1 & 0 & \vdots & -G_{ue} & -G_{up} \\ 0 & 1 & \vdots & -G_{\theta e} & -G_{\theta p} \end{bmatrix} \cdot \begin{bmatrix} u_c \\ \theta_c \\ \cdots \\ \delta_e \\ \delta_p \end{bmatrix} \tag{4}$$

$$\begin{bmatrix} \delta_e \\ \delta_p \end{bmatrix} = \begin{bmatrix} K_{eu} & K_{e\theta} \\ K_{pu} & K_{p\theta} \end{bmatrix} \cdot \begin{bmatrix} e_u \\ e_\theta \end{bmatrix} \tag{5}$$

The closed-loop system is $\boldsymbol{z} = H\boldsymbol{w}$, where $\boldsymbol{z} = [u \;\; \theta]^T$, $\boldsymbol{w} = [u_c \;\; \theta_c]^T$, and H is denoted by:

$$H = \begin{bmatrix} H_{uu} & H_{u\theta} \\ H_{\theta u} & H_{\theta\theta} \end{bmatrix}$$

Now we can use the integrated framework to evaluate the individual control channel specification. More importantly, we have a useful tool to evaluate the system performance, and to make decisions on control integration architecture. Considering that all local channel design objectives have been achieved, so that their respective (ideal) closed-loop transfer functions are available, we will use the proposed integrated framework to select the proper integration architecture, where the decentralized controller becomes:

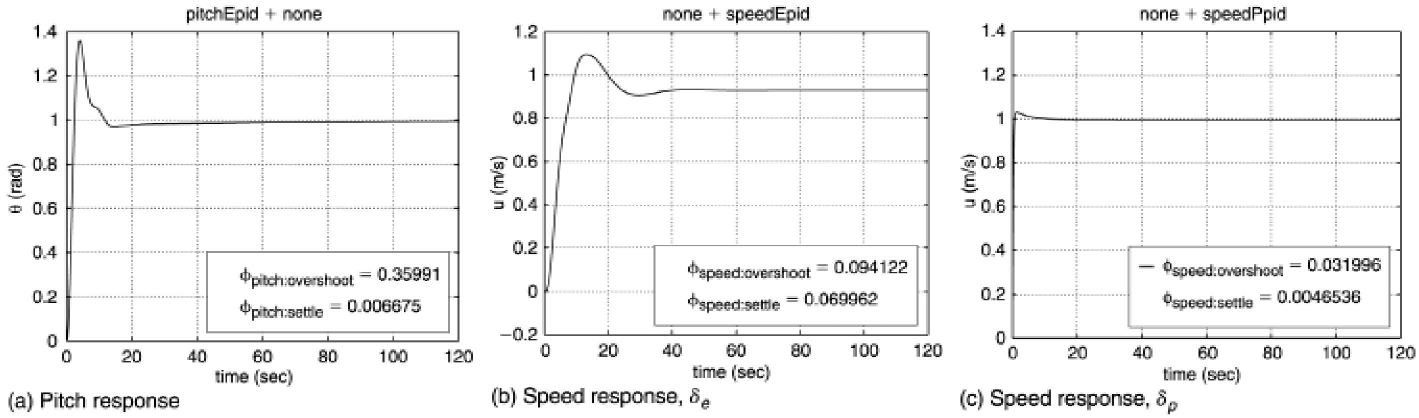

Figure 5. Local pitch and speed PID control.

$$K = \begin{bmatrix} K_{eu} & K_{e\theta} \\ K_{pu} & K_{p\theta} \end{bmatrix} = \begin{bmatrix} 0 & K_{e\theta} \\ K_{pu} & 0 \end{bmatrix} \quad \text{as in Fig. 3(a)} \quad (6)$$

and:

$$K = \begin{bmatrix} K_{eu} & K_{e\theta} \\ K_{pu} & K_{p\theta} \end{bmatrix} = \begin{bmatrix} K_{eu} & K_{e\theta} \\ 0 & 0 \end{bmatrix} \quad \text{as in Fig. 3(b)} \quad (7)$$

respectively. In either of the controller structure, our integration expectation is to have their respective closed-loop transfer functions closer to or better than the local ones. This design objective can be formulated as the following problem statement:

Decentralized Control Integration Problem Statement. Choose decentralized control structure (6) or (7), and further design K_{pu}, $K_{e\theta}$, or K_{eu}, $K_{e\theta}$ accordingly, such that:

$$H_{\theta\theta} \approx L_{\theta\theta} \quad \text{or} \quad \begin{cases} \phi_{pitch:overshoot}(H_{\theta\theta}) \leq \phi_{pitch:overshoot}(L_{\theta\theta}) \leq \alpha_1 \\ \phi_{pitch:sse}(H_{\theta\theta}) \leq \phi_{pitch:sse}(L_{\theta\theta}) \leq \alpha_2 \end{cases} \quad (8)$$

$$H_{uu} \approx L^p_{uu} \quad \text{or} \quad \begin{cases} \phi_{speed:overshoot:p}(H_{uu}) \leq \phi_{speed:overshoot:p}(L^p_{uu}) \leq \beta_1 \\ \phi_{speed:sse:p}(H_{uu}) \leq \phi_{speed:sse:p}(L^p_{uu}) \leq \beta_2 \end{cases} \quad (9)$$

or:

$$H_{uu} \approx L^e_{uu} \quad \text{or} \quad \begin{cases} \phi_{speed:overshoot:e}(H_{uu}) \leq \phi_{speed:overshoot:e}(L^e_{uu}) \leq \gamma_1 \\ \phi_{speed:sse:e}(H_{uu}) \leq \phi_{speed:sse:e}(L^e_{uu}) \leq \gamma_2 \end{cases} \quad (10)$$

Remark 1: After the control integration, if the closed-loop transfer function is close to the local ideal one, we expect the design specifications will be maintained. Furthermore, if the control integration exceeds design specifications, by taking advantage of the integrated control interactions, then the controllers are of course also acceptable.

Remark 2: We do not address the interactions between subsystems, such as $H_{u\theta}$ and $H_{\theta u}$ in this case. First, the focus here is to maintain similar local channel design specifications after control integration. Second, the coupling or interactive effects themselves become additional design specifications that require special attention in design, which is beyond the scope of this investigation. The author has conducted some studies on this topic [10, 11] separately; references therein outline the research progress in that specific field. As a matter of fact, the pitch and speed control example presented in this work shows a strong coupling term on $H_{\theta u}$, but that on $H_{u\theta}$ is negligible. One may use the one-way coupled strategy, or design a special coupling controller, to decouple the cross-effects.

Here the author proposes two approaches to address the decentralized control integration problem statement: the open-loop integration approach and the closed-loop integration approach.

4. Open-Loop Integration

By *open-loop integration*, we imply a forward integration approach: the designer takes the local channel designed controllers $J_{pu}, J_{e\theta}$, and J_{eu}, and integrates directly into the control structure (6) or (7).

4.1 Integration of $\boldsymbol{\delta_e \rightarrow \theta}$ Channel and $\boldsymbol{\delta_e \rightarrow u}$ Channel

The controller (7) becomes:

$$\begin{bmatrix} K_{eu} & K_{e\theta} \\ 0 & 0 \end{bmatrix} = \begin{bmatrix} \bar{\mu} J_{eu} & \mu J_{e\theta} \\ 0 & 0 \end{bmatrix} \quad (11)$$

where $\mu, \bar{\mu}$ are weight coefficients that are used for tuning. The closed-loop transfer matrix becomes:

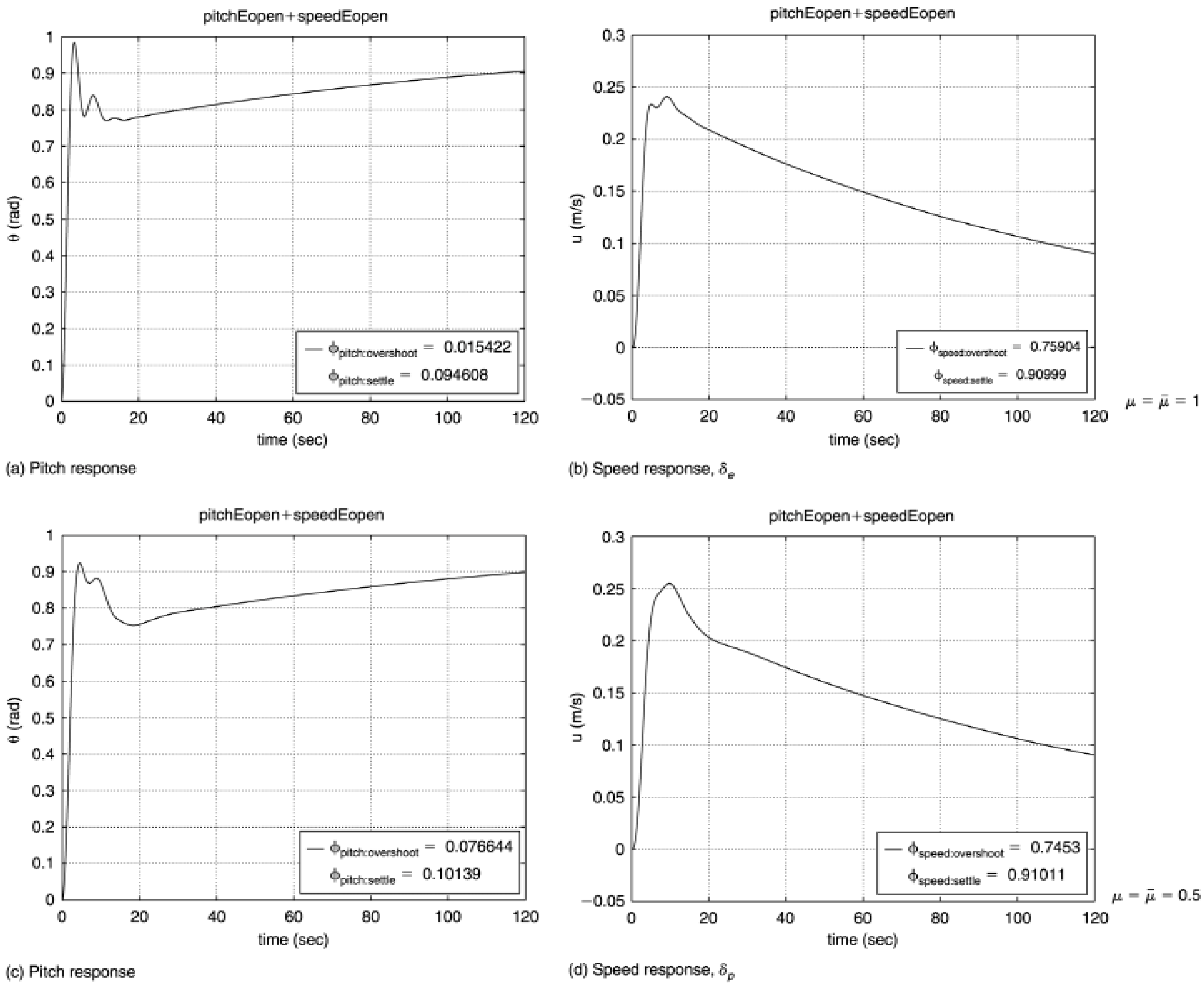

Figure 6. Open-loop integration of $\delta_e \to \theta$ and $\delta_e \to u$ channels.

$$H = \frac{1}{\Delta}\begin{bmatrix} \bar{\mu}G_{ue}J_{eu} & \mu G_{ue}J_{e\theta} \\ \bar{\mu}G_{\theta e}J_{eu} & \mu G_{\theta e}J_{e\theta} \end{bmatrix} \tag{12}$$

and:

$$\Delta = 1 + \mu G_{\theta e}J_{e\theta} + \bar{\mu}G_{ue}J_{eu} \tag{13}$$

Then the problem statements (8) and (10) are described as:

$$\frac{\mu G_{\theta e}J_{e\theta}}{1 + \mu G_{\theta e}J_{e\theta} + \bar{\mu}G_{ue}J_{eu}} \approx L_{\theta\theta}$$
$$\frac{\bar{\mu}G_{ue}J_{eu}}{1 + \mu G_{\theta e}J_{e\theta} + \bar{\mu}G_{ue}J_{eu}} \approx L^e_{uu} \tag{14}$$

One may try to tune the coefficients μ and $\bar{\mu}$ to achieve the above equation. Generally speaking, the freedom and flexibility are very limited. In our numerical example, two cases are presented: (1) set $\mu = \bar{\mu} = 1$; (2) set $\mu = \bar{\mu} = 0.5$. Simulation results are shown in Figs. 6(a), 6(b), and 6(c), 6(d), respectively, which clearly show that open-loop integration is sensitive to the choice of weight factors and the performance is not guaranteed. Proper selection of the coefficients μ and $\bar{\mu}$ depends on the designer's experience, and a bit of luck.

4.2 Integration of $\delta_e \to \theta$ Channel and $\delta_p \to u$ Channel

Similarly, the controller (6) becomes:

$$\begin{bmatrix} K_{eu} & K_{e\theta} \\ 0 & 0 \end{bmatrix} = \begin{bmatrix} 0 & \mu J_{e\theta} \\ \bar{\mu}J_{pu} & 0 \end{bmatrix} \tag{15}$$

with weight coefficients $\mu, \bar{\mu}$. A similar analysis as in Section 4.1 results in an identical challenge, that is, to select proper coefficients μ and $\bar{\mu}$ to solve the problem

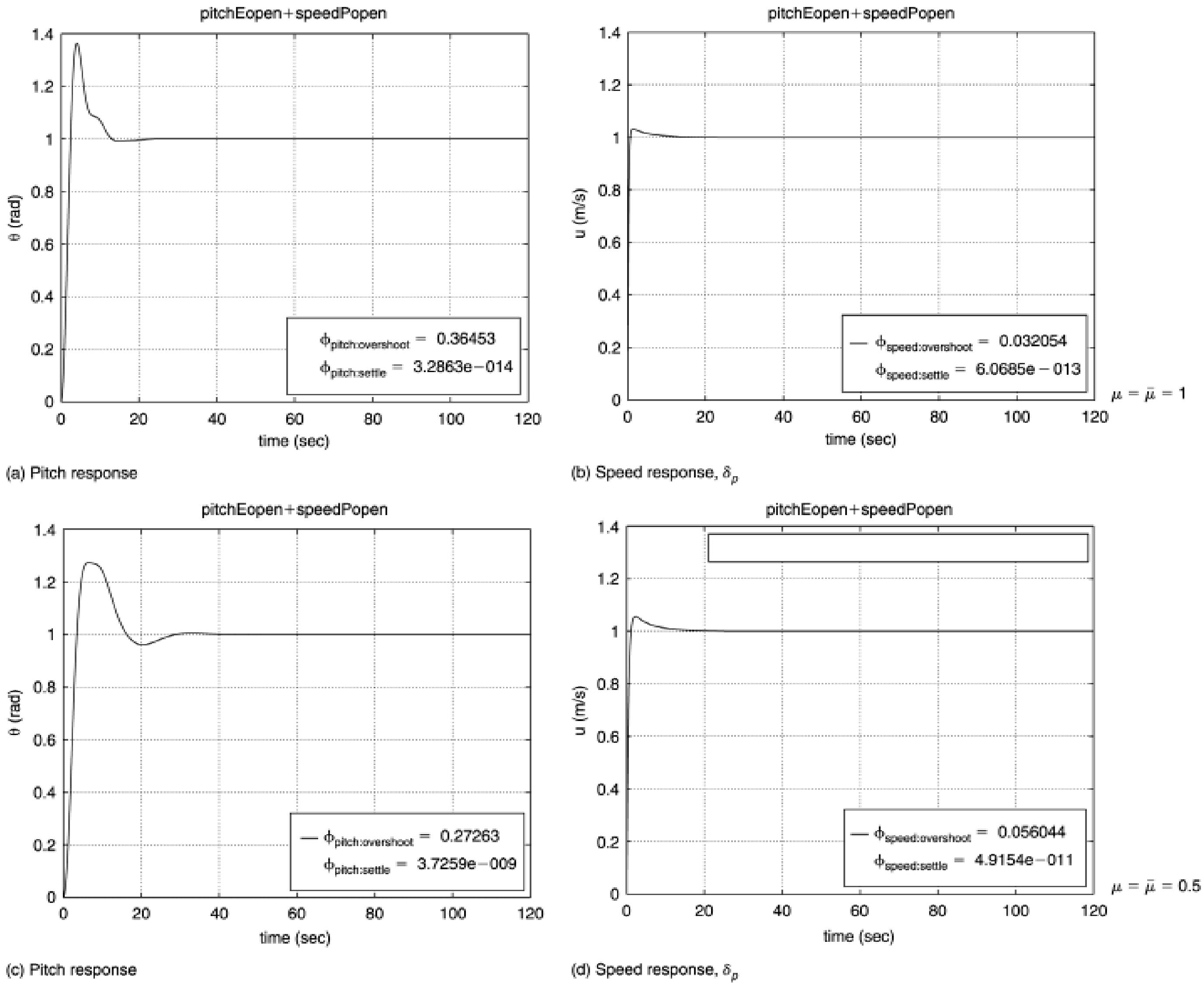

Figure 7. Open-loop integration of $\delta_e \to \theta$ and $\delta_p \to u$ channels.

statements (8) and (9). In our numerical example, the same two cases are presented: (1) set $\mu = \overline{\mu} = 1$; (2) set $\mu = \overline{\mu} = 0.5$. Simulation results are shown in Figs. 7(a), 7(b), and 7(c), 7(d), respectively. The simulation results show that the integration of the $\delta_e \to \theta$ channel and the $\delta_p \to u$ channel provides a better choice, due to its clearly decoupled structure in (6). However, the fluctuation of performance is still very sensitive to those weight factors.

5. Closed-Loop Integration

The *closed-loop integration* refers to a different, reverse integration approach. The designer takes care of the closed-loop transfer functions first, by trying to match the desired local ones. Then the designer reconstructs the decentralized controllers to achieve the closed-loop matrix. Compared to the open-loop integration approach, the closed-loop integration approach promises to address the final performance specifications directly.

5.1 Integration of $\boldsymbol{\delta_e \to \theta}$ Closed-Loop Channel and $\boldsymbol{\delta_e \to u}$ Closed-Loop Channel

The local pitch control channel, under the integration framework, becomes:

$$\begin{bmatrix} K_{eu} & K_{e\theta} \\ K_{pu} & K_{p\theta} \end{bmatrix} = \begin{bmatrix} 0 & J_{e\theta} \\ 0 & 0 \end{bmatrix} \tag{16}$$

and the closed-loop matrix becomes:

$$H_{\theta,\delta_e} = \frac{1}{1 + G_{\theta e} J_{e\theta}} \begin{bmatrix} 0 & G_{ue} J_{e\theta} \\ 0 & G_{\theta e} J_{e\theta} \end{bmatrix} = \begin{bmatrix} 0 & \frac{G_{ue} J_{e\theta}}{1 + G_{\theta e} J_{e\theta}} \\ 0 & L_{\theta\theta} \end{bmatrix} \tag{17}$$

The local speed control channel (through elevator), under the integration framework, becomes:

$$\begin{bmatrix} K_{eu} & K_{e\theta} \\ K_{pu} & K_{p\theta} \end{bmatrix} = \begin{bmatrix} J_{eu} & 0 \\ 0 & 0 \end{bmatrix} \tag{18}$$

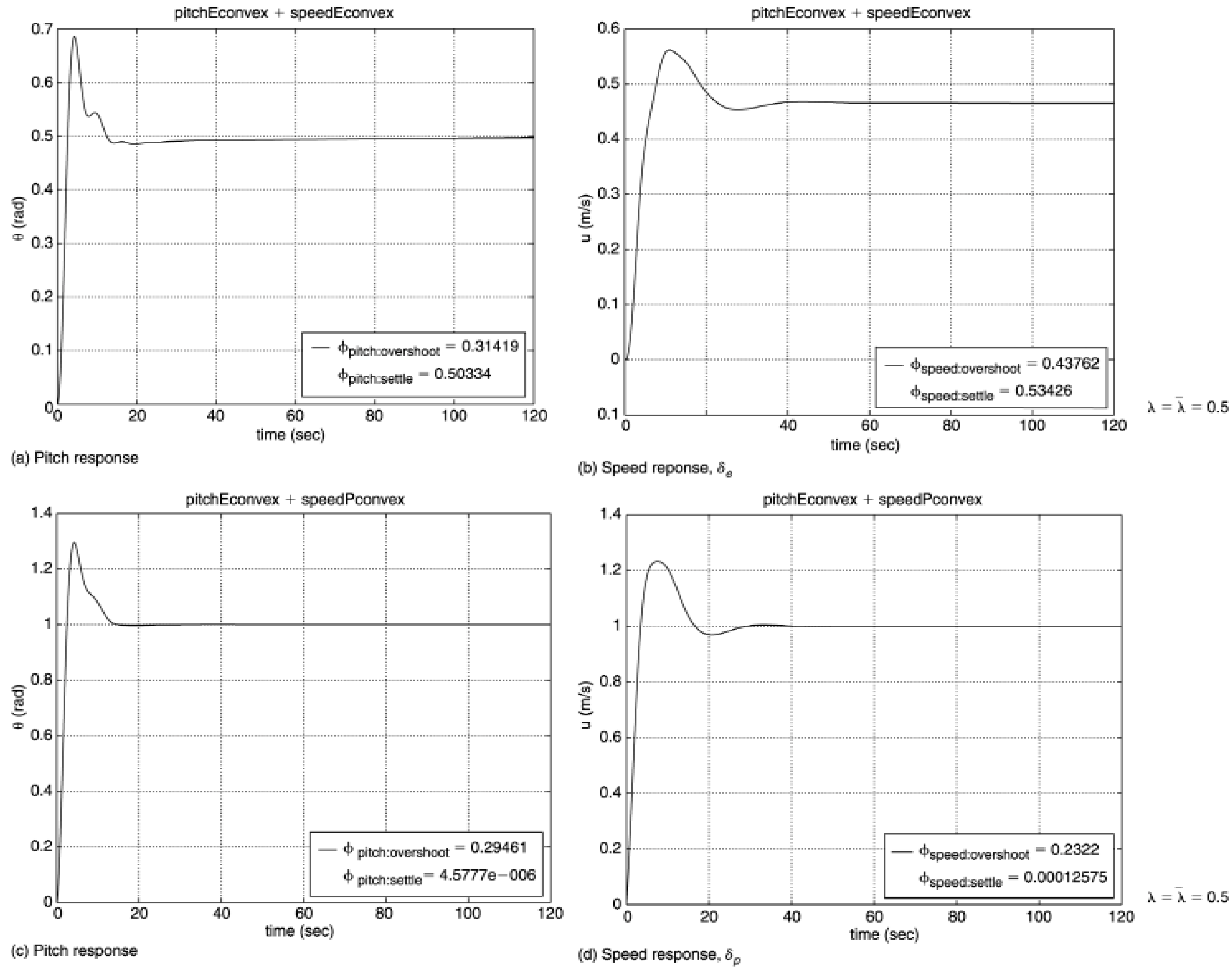

Figure 8. Closed-loop convex integration.

and the closed-loop matrix becomes:

$$H_{u,\delta_e} = \frac{1}{1+G_{ue}J_{eu}} \begin{bmatrix} G_{ue}J_{eu} & 0 \\ G_{\theta e}J_{eu} & 0 \end{bmatrix} = \begin{bmatrix} L^e_{uu} & 0 \\ \frac{G_{\theta e}J_{eu}}{1+G_{ue}J_{eu}} & 0 \end{bmatrix} \tag{19}$$

Obviously, a closed-loop integration

$$H = H_{\theta,\delta_e} + H_{u,\delta_e} \tag{20}$$

would lead to a perfect match of the local closed-loop transfer functions: $H_{uu} = L^e_{uu}$ and $H_{\theta\theta} = L_{\theta\theta}$. This would in turn solve the problem statements (8) and (10). Unfortunately, the direct derivation of $K_{e\theta}$ and K_{eu} based on the above H leads to unstable controllers. Therefore, we propose an alternative, *convex closed-loop integration* method:

$$H = \lambda H_{\theta,\delta_e} + \bar{\lambda} H_{u,\delta_e} \tag{21}$$

where $\lambda, \bar{\lambda} > 0,\ \lambda + \bar{\lambda} = 1$. The convex coefficients can be used to improve the design specifications as in the problem statements (8) and (10). Mathematical manipulation gives the following stabilizing controller formula:

$$K_{e\theta} = \frac{J_{e\theta}}{1 + \bar{\lambda}/\lambda \frac{1+G_{\theta e}J_{e\theta}}{1+G_{ue}J_{eu}}} \tag{22}$$

$$K_{eu} = \frac{J_{eu}}{1 + \lambda/\bar{\lambda} \frac{1+G_{ue}J_{eu}}{1+G_{\theta e}J_{e\theta}}} \tag{23}$$

Remark: The advantages of the closed-loop integration can be demonstrated by studying the expressions of the designed controllers K_{eu} and $K_{e\theta}$. First of all, these two controllers are derived based on a desired closed-loop transfer matrix H, which guarantees the specification reservation under the integrated framework. Second, these two controllers are actually "calculated," without tuning efforts such as those in the case of open-loop integration, that is, K_{eu} and $K_{e\theta}$ are no longer the same as the original local controllers J_{eu} and $J_{e\theta}$, or proportional to their weighted version $\bar{\mu}J_{eu}$ and $\mu J_{e\theta}$. Instead, (22) and (23) provide a new control structure that cannot be obtained by the open-loop integration approach. Third, it is worth pointing out that K_{eu} and $K_{e\theta}$ are still decentralized controllers, making it easy for local implementation.

Choosing $\lambda = \overline{\lambda} = 0.5$ in our numerical example, one obtains the decentralized controllers, and simulation results are presented in Figs. 8(a) and 8(b). This shows that the closed-loop integration is far superior to open-loop integration in our example, notably in achieving better and more balanced design specifications.

5.2 Integration of $\delta_e \rightarrow \theta$ Closed-Loop Channel and $\delta_p \rightarrow u$ Closed-Loop Channel

The closed-loop convex integration of the local speed control channel (through throttle) and the local pitch control channel will result in controllers the K_{pu} and $K_{e\theta}$, which resemble the expressions of (23) and (23), respectively. Again, in our numerical example, the controller is derived as follows, using the same $\lambda = \overline{\lambda} = 0.5$ convex factors, and simulation results are presented in Figs. 8(c) and 8(d). The closed-loop integration performs better than the open-loop integration, being less sensitive.

6. Performance Evaluation

With choices between $\delta_e \rightarrow u$ and $\delta_p \rightarrow u$ channels, and selections between open-loop and closed-loop integration approaches, there are multiple combinations to choose. From the performance evaluation point of view, we compare those options by judging their achieved design specifications. As the interest of this paper is in investigating how the local design specifications are maintained after the control integration, we use the design specifications achieved by the local designed controllers, shown in simulation plots, as the criteria. When the specification values are equal or better (smaller) than their respective local channel achieved ones (the first three rows), the integration is deemed successful. The data show that the choice of integration between pitch control $\delta_e \rightarrow \theta$ and speed control through throttle $\delta_p \rightarrow u$ channels generally performs better than the other ones. It is clear from (6) and Fig. 3(a) that this is partly due to decoupling controller structure. The unfavourable ones all contain some level of coupling controllers, and therefore "fight" for the same elevator control input δ_e. Within the same control architecture, the open-loop integration is more sensitive to the tuning weight parameters in terms of performance specifications. The challenge is to find a good trade-off between the two design specifications. On the other hand, the closed-loop integration approach provides a well-balanced solution. It is also less ad hoc from the design point of view.

7. Conclusion

Both the proposed open-loop integration and the closed-loop integration approaches can be applied to the decentralized control design and implementation. Performance analysis and evaluation are better obtained from an integrated control framework. Choosing the candidate local channels for integration should become part of the decision-making process during the integration practice.

The open-loop approach can incorporate the local designed controllers directly. However, it suffers from the sensitive tuning efforts, and the specifications under the integrated framework are not guaranteed. On the other hand, controller design based on the closed-loop convex integration approach can be automated without an empirical tuning process. Unfortunately, it may lead to high-order complex control law that will require much more computing power. Our study of the integrated pitch and speed control suggests that closed-loop integration is more promising and is worth further investigation.

The proposed integration approaches have their own limitations. First of all, the integration is applied based on the assumption that all local design has been completed and optimized. Second, the focus of this work is on the local specification preservation under the integrated structure, instead of the overall system performance. Specifically, the interacting effects during integration are not taken into account. Third, the most promising closed-loop integration $H = H_{\theta,\delta_e} + H_{u,\delta_e}$ leads to an unstable controller structure. There may exist other design techniques to find a stabilizing controller and to achieve this desired H. All these issues, among others, are currently being investigated by the author.

References

[1] D. McRuer, I. Ashkenas, & D. Graham, *Aircraft dynamics and automatic control* (Princeton University Press, 1973).

[2] S. Garg & D. Mattern, Integrated flight/propulsion control system design based on a centralized approach, *AIAA Journal of Guidance, Control, and Dynamics*, *14*(1), 1991, 107–116.

[3] S. Garg, Partitioning of centralized integrated flight/propulsion control design for decentralized implementation, *IEEE Trans. on Control Systems Technology*, *1*, June 1993, 93–100.

[4] D. Bates & I. Postlethwaite, Integrated control system design for the automotive industry using modern robust control methods, *Proc. IEE Colloquium on System Control Integration and Rapid Prototyping in the Automotive Industry*, 1997, 1–6.

[5] W. Neighbors III & S. Rock, Integrated flight/propulsion control-subsystem specifications for performance, *AIAA Journal of Guidance, Control, and Dynamics*, *8*(3), 1995, 572–578.

[6] R.C. Nelson, *Flight stability and automatic control*, 2nd ed. (WCB McGraw-Hill, 1998).

[7] B. Etkin & L. Reid, *Dynamics of flight: Stability and control*, 3rd ed. (John Wiley and Sons, 1996).

[8] H. Liu & J. Mills, Robot trajectory control system design for multiple simultaneous specifications: Theory and experimentation, *Journal of Dynamic Systems, Measurement, and Control*, *120*, 1998, 520–523.

[9] H.H. Liu, Multi-objective integrated flight control, paper presented at AIAA Guidance, Navigation, and Control Conference & Exhibit, August 2001, Paper A01-37501.

[10] A. de Ruiter & H.H. Liu, Integrated multiple objective controller: Design for one-way coupled systems, *Proc. of American Control Conf.*, Denver, CO, June 4–6, 2003, 5179–5184.

[11] A. de Ruiter & H.H. Liu, Control design decoupling for two-way coupled systems, *Proc. IEEE Conf. on Control & Applications*, Taipei, Taiwan, ROC, September 2–4, 2004.

Biography

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