

# Development of a Distributed Multi-MCU Based Flight Control System for Unmanned Aerial Vehicle

Jaw-Kuen Shiau\*, Wei-Sheng Hung and Cheng-Min Chang

*Department of Aerospace Engineering, Tamkang University,  
Tamsui, Taiwan 251, R.O.C.*

## Abstract

This paper presents the design of a distributed multi-microcontroller based computing framework for UAV application. A DSPIC microcontroller (MCU) based system architecture is established first. The system contains three major parts, namely, sensing and attitude determination section, control section, and ground section. The sensing and attitude determination section consists of four circuit boards (master control board, slave control board, sensor board, and power supply board) of identical size (5 cm × 5 cm). The sensor board contains three axes inertial measurement unit, electronic compass unit, and a GPS receiver. The sensors and the DSPIC MCUs are connected via an I<sup>2</sup>C (inter-integrated circuit) data bus with the DSPIC of the master control board acting as the master MCU. Modular design was used to combine the master and slave control boards to form the system's control section and to facilitate system expansion for accommodating additional avionics functions. UART interface was used for inter-section communication. Results of the design and simulation of a model-based flight control system with time delay were also included to demonstrate the success of the design of the distributed multi-MCU based flight control system.

**Key Words:** Distributed Control System, State Feedback, Delay Compensation, UAV

## 1. Introduction

Single chip microcontroller units (MCU) have been widely applied in our daily lives and could be used in household electronics and utensils, industrial controllers, and medical equipment. Advancements in technology and increasing demands in processing power meant that MCUs must provide better functions and faster calculations in order to satisfy design and application requirements. DSPIC is a new generation 16 bit MCU that provides the advantages of faster processing speeds and increased executable processing capacity. When coupled with large increases in memory sizes, DSPIC would be a useful tool for numerous applications and designs.

The usefulness of unmanned aerial vehicles (UAV) is dependent on its capability of autonomous flight. The Avionics and Flight Simulation Lab (AFSL) and Un-

manned Aerial Vehicles Lab (UAV Lab) under the Aerospace Department of Tamkang University has been developing avionics systems for many years. After careful consideration, MCUs is chosen as the platform for developing avionics and flight control systems mainly because of their low cost. The entire system was developed and manufactured independently in the lab in order to reduce costs. Another reason for our choice was the low development prerequisites. In order to help beginners become proficient in the development tools, we utilized the MCU PIC<sup>®</sup> series produced by Microchip as well as the corresponding development software CCS C Compiler<sup>®</sup>. Programming was also made more comprehensive and provided efficient learning of the processes and techniques of MCU program design through the use of program libraries, greatly reducing development cycle time. In order to achieve the design requirements of effective navigation control and autonomous flight, our flight control system included multiple MCUs capable of

---

\*Corresponding author. E-mail: shiauj@mail.tku.edu.tw

processing various flight data and exert corresponding control. I<sup>2</sup>C (inter-integrated circuit) communication interface was also utilized to create an independent networked control system needed to overcome the issue of data exchange between MCUs. Networked control system is a form of distributed control system. The sensors, actuators, and controllers would use a common communication network to connect to each other. Sensor and control signals within the control system would be transmitted digitally via the network in closed feedback loops. Hence, every node in the networked control system would be directly connected to the control network. Advantages of the networked control system include simpler wiring and more flexible structural layouts as well as improving the ease of system expansion, maintenance, and achieving data sharing.

However, networked control systems have their own disadvantages. These include delays in data transmission processes, loss of data packets, and stability issues. Time delay issues of networked control systems have been subject to widespread discussion in recent years [1–6]. In [1], several recent results on estimation, analysis, and controller synthesis for network control systems were reported. Issues of network-induced delay (constant or time varying) and methods of delay compensation were presented in [2]. Problems and opportunities arising due to delays were examined in [3]. State feedback controller design of networked control systems with interval time-varying delay and nonlinearity was discussed. Stability analysis and model based control systems design with time delay were reported in [5,6].

In-depth investigations on the effects of using network controls had not been carried out for UAVs designed in [7,8]. In [9], we carried out further investigations on the distributed flight control systems of our UAV [7,8]. Distributed multi-MCU based computing architectures offer numerous advantages in the development of complex systems [10–13]. This investigation would utilize the theoretical basis described in [5–9] to develop a distributed multi-MCU flight control system [14]. The paper is mainly divided into two parts: the first deals with the design environment of the distributed multi-MCU flight control system using DSPIC as the main processing core; the second part deals with the design and analysis of model-based flight controller. We divided the distributed multi-MCU control system into three sections: the sensing and attitude determination section, the con-

trol section, and the ground section. I<sup>2</sup>C was used as the major means of communication between individual chips. Any inadequacy would be supplemented using UART. Modular designs were also used to achieve the objectives of hardware expandability and design flexibility. The model-based flight controller designs included a state feedback time compensation controller to deal with the inevitable time delay problem of the network control system. A plant model was used to simulate plant behavior during the periods when sensor data is not available. As the controller would only receive sensor data transmitted by the sensor after a time delay, a propagation unit was employed in the control system to propagate the sensor signals to the present time. The estimate was then used to update the model which in turn generates the control signal for the UAV. The design was analyzed and the controller was successfully verified in Matlab.

## 2. System Architecture

The distributed multi-MCU control system investigated in this paper is shown in Figure 1. The system has been divided into three modules: the sensing and attitude determination section, the control section, and the ground section. I<sup>2</sup>C was used as the major means of communication between individual chips. Any inadequacy would be supplemented using UART. The designs mainly used a single system as the major framework. This system would be expanded to other parts, allowing the use of programming to change the system functions. Inertial measurement devices and GPS were used as the main sensors. The main processing chip used was Microchip's DSPIC33F series MCU.

The sensing and attitude determination section used in this project included a GPS receiver and inertial measurement module. The GPS receiver used was the EVM-GPS-R4 from LINX. The inertial measurement module included two chips, namely the LSM303DLHC (that includes a magnetic compass and accelerometer) and L3GD20 (gyroscope) developed by STMicroelectronics. For attitude determination, an algorithm, which has been validated using actual flight data [15], has been adopted and shown in Figure 2. The algorithm uses the GPS and inertial data to calculate and quantify the gravitational field. The results would then be used as the measurement for the Kalman filter to determine the attitude.

System hardware design was also divided into four

sections, which included the power control board, sensor board, master control board, and the slave control board.

Figures 3 to 6 show actual photos of the completed system. In particular, Figure 5 displays the top side of the

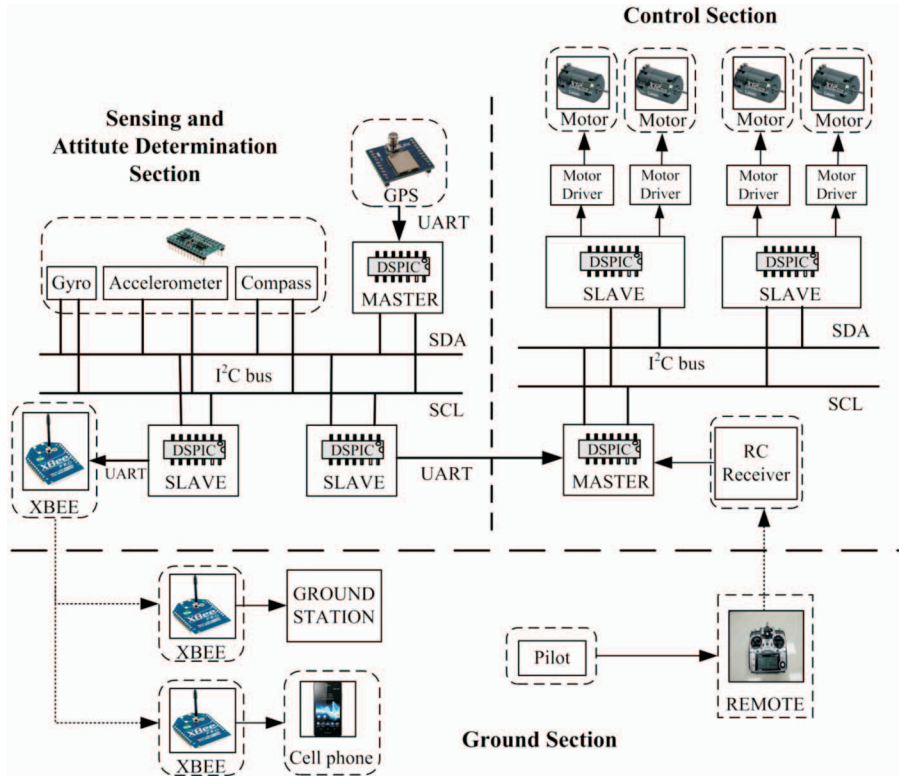


Figure 1. System architecture of the distributed multi-MCU based flight control system.

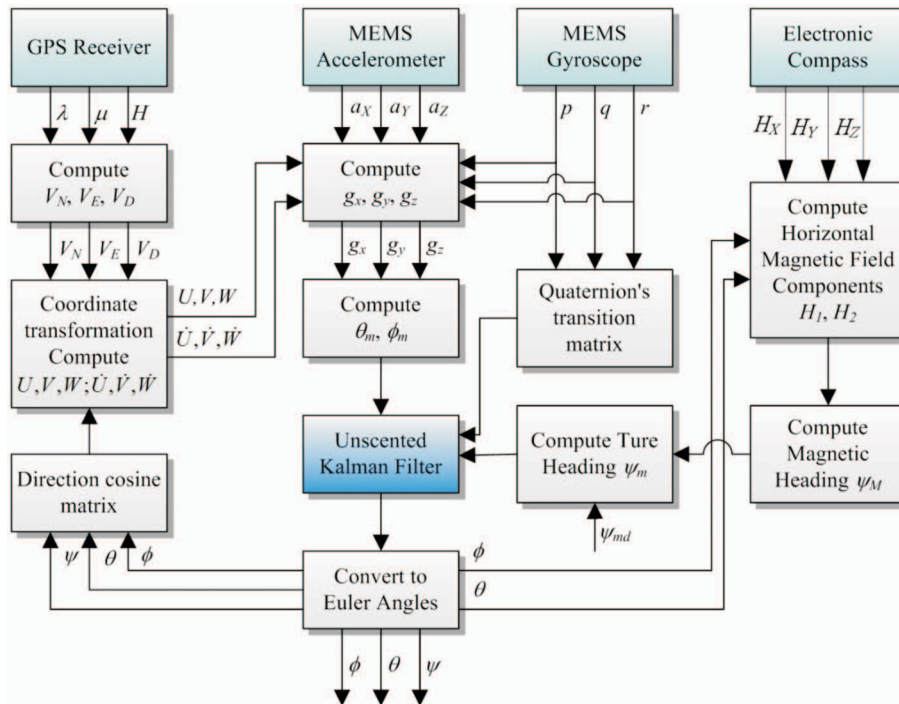
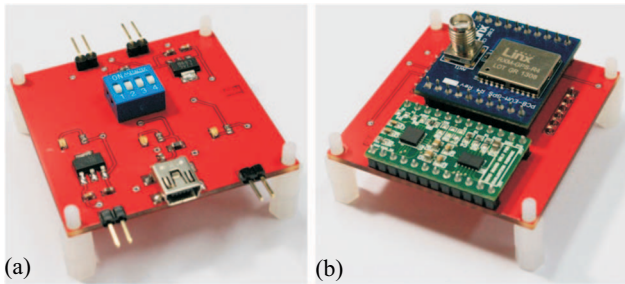
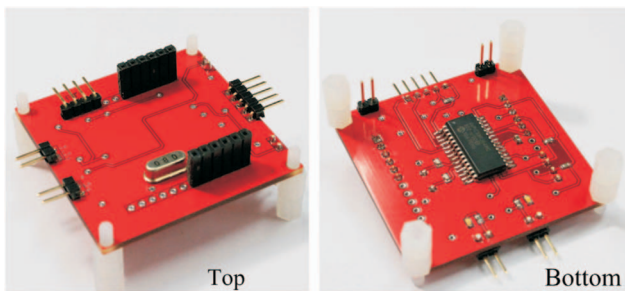


Figure 2. Attitude estimation algorithm [15].



**Figure 3.** (a) Power control board; (b) Sensor board.



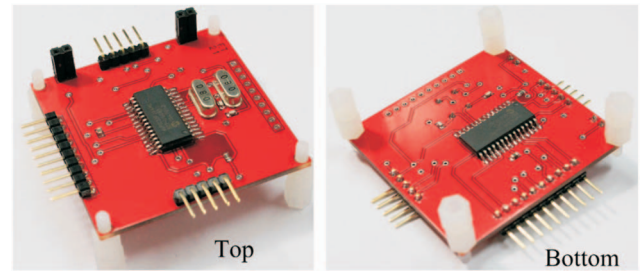
**Figure 4.** Master control board.

slave control board. The reverse side has another MCU similar to the one used on the top side. To ensure easy assembly, the four circuit boards were designed to the same dimension ( $5\text{ cm} \times 5\text{ cm}$ ) and were capable of independent processing provided that the required voltage was supplied. Since the sensor board was designed to be replaceable by GPS units of higher sampling frequencies, a replaceable socket was hence utilized.

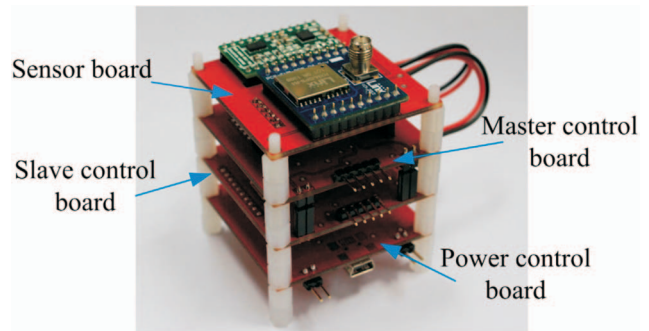
The major design principle of the power control board was to ensure that the system has an independent power source instead of relying on other systems. Three types of power sources were designed: USB, power supplier, and battery. Power output could be provided using a set of 5 V and 3.3 V source. The circuit board included a DIP switch that functions as an on/off switch as well as the reset button. The sensor board houses the inertial measurement module and GPS receiver.

The master control board has an MCU designed to function as the I<sup>2</sup>C MASTER. If other functions are required, the remaining I/O pins could be used. The master control board also has a number of I<sup>2</sup>C connections for future expansion for sensors or MCU interfaces that require I<sup>2</sup>C transmission.

The slave control board has two MCUs designed to act as the I<sup>2</sup>C SLAVE. Since the I<sup>2</sup>C pins of the two MCUs were connected in series, they could also be used



**Figure 5.** Slave control board.



**Figure 6.** Sensing and attitude determination unit.

as an independent control board by delegating one MCU as the MASTER and the other as the SLAVE. The slave control board design also includes additional outputs that could be used to connect to wireless transmission modules such as Bluetooth or X-bee. Since our system has designed the two MCUs to be capable of transmitting the same data, both MCUs were therefore designed with additional TX and RX. Additionally, the slave control board could independently control the motors.

The four circuit boards (Figures 3 to 6) could be assembled together to form the completed sensing and attitude determination module (Figure 1). To obtain a control module, one only needs to remove the sensor board from the system. The control module would provide flight control functions. Attitude angles and data would be transmitted by the sensing and attitude determination module via UART. Since modular designs were used, we could expand the system using the similar hardware connections to support other avionics functions and requirements as shown in Figure 7.

### 3. State Feedback Control System with Time Delay

The distributed multi-MCU control system investi-



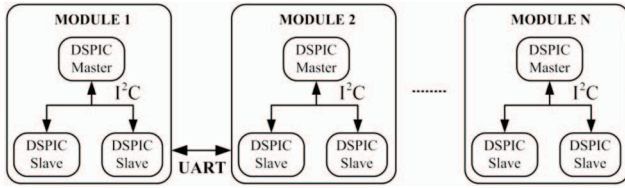


Figure 7. Modular system design and expansion.

gated in this paper utilizes I<sup>2</sup>C communication protocols to transmit data. Time delay during data transmission in networked control systems would be inevitable. Hence, time delay issues must be thoroughly considered during design phases. The following section investigates the design of networked control system with time delay.

This section shall first describe the state feedback control system. We start with the assumption that all system states could be measurable. However, distributed designs meant that time delay would be experienced between data transmission by the sensor and data receiving by the controller. Thus, a state propagation unit (time delay compensator) was used to simulate system states with the time delay. The state feedback control system with time delay is shown in Figure 8.

The following explains the various blocks illustrated in Figure 8:

$$\text{Plant: } \dot{x}(t) = Ax(t) + Bu(t) \quad (1)$$

Plant represents the linearized vehicle dynamic system.

$$\text{Model: } \dot{\hat{x}} = A\hat{x}(t) + Bu(t) \quad (2)$$

We would use this Model to simulate the system state and produce the control command

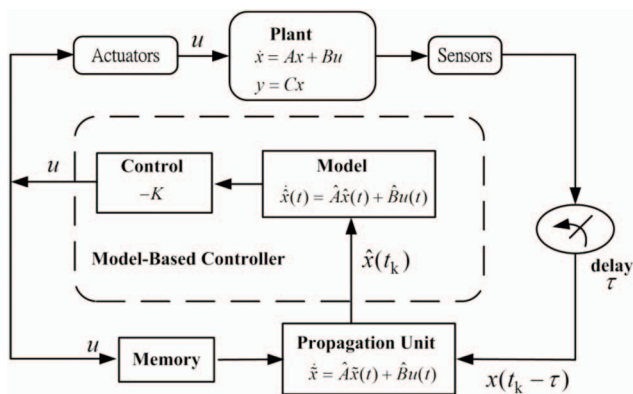


Figure 8. State feedback control system with time delay.

$$u(t) = -K\hat{x}(t), t \in [t_{k-1}, t_k] \quad (3)$$

The dynamic model of the state propagation unit would be

$$\dot{\tilde{x}}(t) = \hat{A}\tilde{x}(t) + \hat{B}u(t), t \in [t_k - \tau, t_k] \quad (4)$$

The update law of the system would thus be

$$\begin{cases} \text{at } t = t_k - \tau & : \tilde{x}(t) \leftarrow x(t) \\ \text{at } t = t_k & : \hat{x}(t) \leftarrow \tilde{x}(t) \end{cases} \quad (5)$$

The state produced by the model  $\hat{x}(t)$  was used to compute the control signal  $u(t)$ . The sequence of the control signals was recorded. Suppose that the controller acquires system state at time  $t_k$ , the received state would be  $x(t_k - \tau)$ . The state propagation unit would use the received signal  $x(t_k - \tau)$  and the recorded command  $u(t)$  issued between  $(t_k - \tau)$  to  $t_k$  for state prediction. By using  $x(t_k - \tau)$  as the initial condition, the unit would instantaneously simulate the state after the time delay and predict the state  $\tilde{x}(t_k)$  at time  $t_k$ , and then send  $\tilde{x}(t_k)$  to the system model to update the system state and calculate a new set of control signals. Details of the state update for time delay compensation is illustrated in Figure 9.

Defining  $\hat{e}(t) = \tilde{x}(t) - \hat{x}(t)$ ,  $\tilde{e}(t) = x(t) - \tilde{x}(t)$ ,  $\tilde{A} = A - \hat{A}$ ,  $\tilde{B} = B - \hat{B}$  and  $\tilde{C} = C - \hat{C}$ , we could rewrite the state space equation for the error  $\hat{e}(t)$ ,  $\tilde{e}(t)$  and the state of the controlled system  $x(t)$  as:

$$\dot{\phi}(t) = \Lambda\phi(t) \quad (6)$$

with

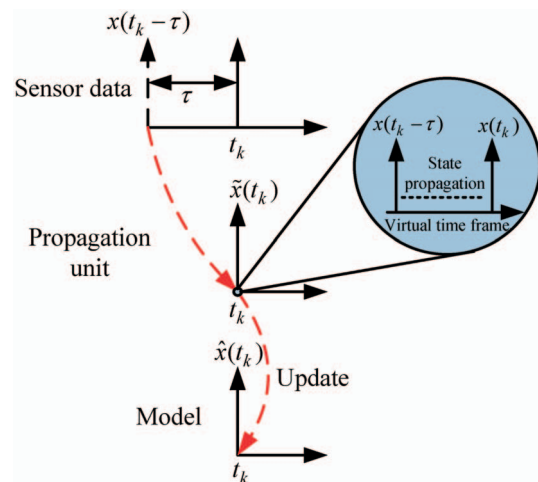


Figure 9. Update law for the state feedback time delay compensation.

$$\phi(t) = \begin{bmatrix} x(t) \\ \tilde{e}(t) \\ \hat{e}(t) \end{bmatrix}; \Lambda = \begin{bmatrix} A - BK & BK & BK \\ \tilde{A} - \tilde{B}K & -\hat{A} + \tilde{B}K & \tilde{B}K \\ 0 & 0 & \hat{A} \end{bmatrix} \quad (7)$$

The necessary and sufficient condition for networked control system stability with propagation unit (time delay compensation system) was reported in [6]. We first divided the dynamics of the propagation unit at time  $t \in [t_k, t_{k+1})$  into two sections. In the first section with time  $t \in [t_k, t_{k+1} - \tau)$  and update law  $\tilde{x}(t) \leftarrow x(t)$ , which would be when the controlled system updates the state of the propagation unit, we hope that the error  $\hat{e}(t)$  between the states of the propagation unit  $\tilde{x}(t)$  and system model  $\hat{x}(t)$  at time  $t_k^-$  to approach 0. In the second section, at time  $t \in [t_{k+1} - \tau, t_{k+1})$  and update law of  $\hat{x}(t) \leftarrow \tilde{x}(t)$ , which is when the propagation unit state updates the system model state, we hope that the error  $\tilde{e}(t)$  between the controlled system state  $x(t)$  and propagation unit state  $\tilde{x}(t)$  at time  $(t_{k+1} - \tau)^-$  to approach 0. This allowed us to obtain:

$$\phi(t) = e^{\Lambda(t-t_k)} M_1 \phi(t_{k-1} - \tau) = e^{\Lambda(t-t_k)} (M_2 M_1)^k \phi(t_0) \quad (8)$$

for  $t \in [t_k, t_{k+1} - \tau)$

and

$$\phi(t) = e^{\Lambda(t-(t_{k+1}-\tau))} (M_2 M_1) \phi(t_k) = e^{\Lambda(t-(t_{k+1}-\tau))} M_1 (M_2 M_1)^k \phi(t_0) \quad (9)$$

for  $t \in [t_{k+1} - \tau, t_{k+1})$

in which

$$M_1 = \begin{bmatrix} I & 0 & 0 \\ 0 & 0 & 0 \\ 0 & I & I \end{bmatrix} e^{\Lambda((t_{k+1}-\tau)-t_k)}, M_2 = \begin{bmatrix} I & 0 & 0 \\ 0 & I & 0 \\ 0 & 0 & 0 \end{bmatrix} e^{\Lambda\tau} \quad (10)$$

Hence, the eigenvalues of  $(M_2 M_1)$  must fall within the unit circle for the system to be stable.

#### 4. Computer Simulation

The longitudinal motion equations of the UAV [9] developed in this lab was subject to digital simulation. Background parameters are shown in Table 1. Simulation was carried out by first writing a real-time simulation program in Matlab and then using the system model described in the following to control the assumed target.

$$\begin{bmatrix} \Delta \dot{u} \\ \Delta \dot{\alpha} \\ \Delta \dot{q} \\ \Delta \dot{\theta} \end{bmatrix} = \begin{bmatrix} -0.108932 & 4.607112 & 0 & -9.8 \\ -0.083864 & -3.926032 & 1.043912 & 0 \\ 0 & -73.471801 & -5.99488 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \Delta u \\ \Delta \alpha \\ \Delta q \\ \Delta \theta \end{bmatrix} + \begin{bmatrix} 0 \\ -0.201883 \\ -42.22549 \\ 0 \end{bmatrix} \Delta \delta_e \quad (11)$$

For the actual aerial vehicle, we assumed a 10% increase in drag compared to the system model and hoped that the controlled system would be able to maintain a stable state during cruising. Matrices A and B of the state space representation are provided in the following:

$$A = \begin{bmatrix} -0.119825 & 4.607112 & 0 & -9.8 \\ -0.083864 & -3.9314821 & 1.043912 & 0 \\ 0 & -73.471801 & -5.99488 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \quad (12)$$

$$B = \begin{bmatrix} 0 \\ -0.201883 \\ -42.22549 \\ 0 \end{bmatrix} \quad (13)$$

While simulating the propagation unit, we also simulated the results if there were no propagation unit used. The sampling frequency of the controller was assumed to be 0.05 seconds. Assuming the time delay to be 0.025 seconds (smaller than the sampling frequency of the controller) and initial states to be  $\Delta\alpha = 10^\circ$ , and  $\Delta\theta = 10^\circ$  with  $K = [0.0486 \ 0.1195 \ -0.1562 \ -0.43]$ , digital simulation results shown in Figures 10 and 11 would be obtained. Figure 10 shows the results if there was no time delay compensation while Figure 11 shows the results if time delay compensation was provided. The red (dotted line) would represent the model while the blue (solid line) would be the plant. We could see that without the propagation unit, the model state would take more time to catch up to the Plane State.

Assuming time delay to be 0.1 seconds (greater than

**Table 1.** Background parameter settings

V (m/s)	15.2876	$I_y$	0.394
S (m <sup>2</sup> )	0.4816	$\theta$ (deg)	4
MAC (m)	0.2367	m (kg)	5.579
$\rho$ (kg/m <sup>3</sup> )	1.225	b (m)	2.0345

the sampling frequency of the controller) and initial states to be  $\Delta\alpha = 10^\circ$  and  $\Delta\theta = 10^\circ$ , the digital simulation results shown in Figures 12 and 13 would be obtained. We could find that without the propagation unit, the initial fluctuations would be more severe especially for speed and pitch angle. If delay time is increased, the situation would be even more severe. However, adding the propagation unit would significantly improve the results.

### 5. Conclusions

This paper used low-cost MCUs to design a distri-

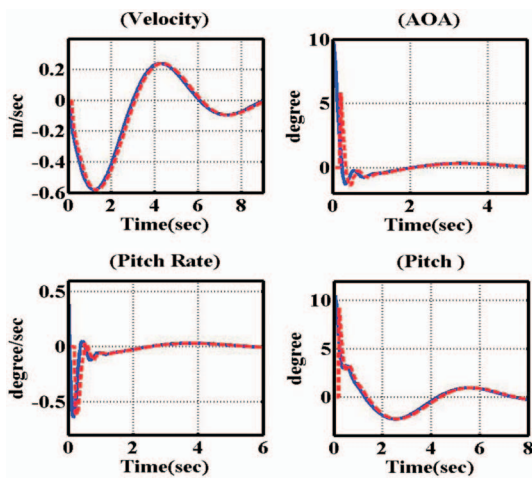


Figure 10. System state without the propagation unit with a time delay of 0.025 seconds (smaller than the controller sampling frequency). Red (dotted line) represents the model, while the blue (solid line) represents the plant.

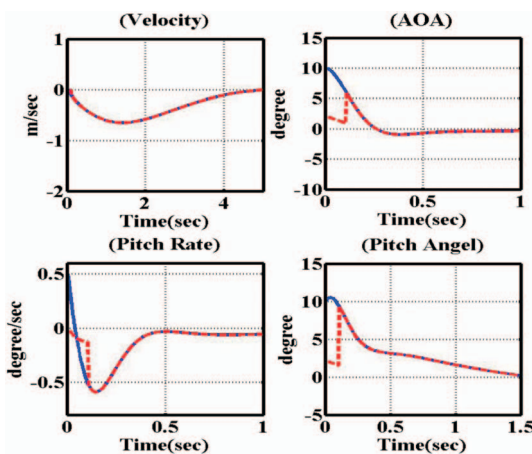


Figure 11. System state when using the propagation unit with a time delay of 0.025 seconds (smaller than the controller sampling frequency). Red (dotted line) represents the model, while the blue (solid line) represents the plant.

buted multi-MCU flight control system for UAVs. This system was composed of three subsystems, namely the sensing and attitude determination module, the control module, and the ground control module. The sensors used include three-axis gyroscopes, accelerometer, digital compass, and a GPS receiver. A multi-chip MCU for DSP calculation functions was used for the core of the designed system. We were thus able to carry out complex non-linear Kalman filters and calculate attitude angle using this system. The sensing and attitude determination module and control module would use USART for

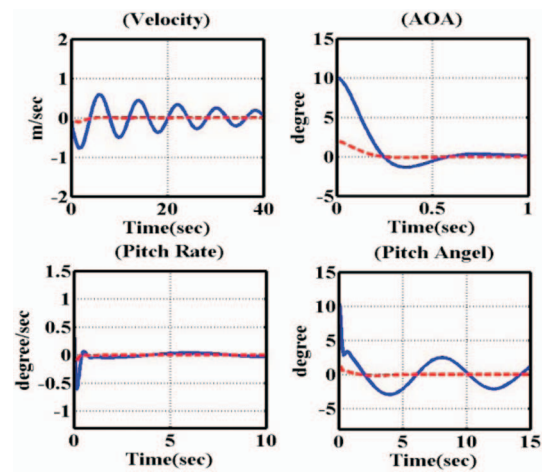


Figure 12. System state without the propagation unit with a time delay of 0.1 seconds (greater than the controller sampling frequency). Red (dotted line) represents the model, while the blue (solid line) represents the plant.

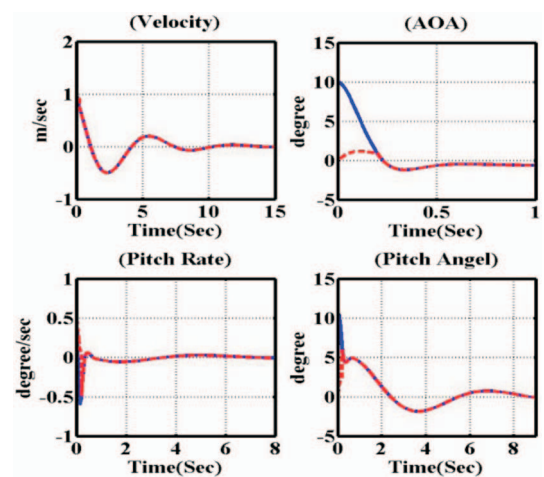


Figure 13. System state when using the propagation unit with a time delay of 0.1 seconds (greater than the controller sampling frequency). Red (dotted line) represents the model, while the blue (solid line) represents the plant.

data transmission. The system has a modular design, thus facilitating the expansion of the system's navigational requirements. This paper also explores the use of dynamic-model networked control systems to process inherent time delay issues. When the control system fails to receive sensor data, the system dynamic model would generate system state data to produce a command. Also, sensor data would have been delayed for a while by the time it is received by the control system. Hence, a data propagation unit was designed to simulate the real-time system state after the time delay and update the system state in the dynamic model so that the control system would not be kept in the open-loop control state. The resulting design was successfully verified in MATLAB.

### Acknowledgement

This research is supported by the National Science Council, Taiwan, Republic of China, under Grant NSC 102-2221-E-032 -017 -.

### References

- [1] Hespanha, J. P., Naghshtabrizi, P. and Xu, Y., "A Survey of Recent Results in Networked Control Systems," *Proceedings of the IEEE*, Vol. 95, No. 1, pp. 138–172 (2007). doi: [10.1109/JPROC.2006.887288](https://doi.org/10.1109/JPROC.2006.887288)
- [2] Zhang, W., Branicky, M. S. and Phillips, S. M., "Stability of Networked Control Systems," *IEEE Control Systems Magazine*, Vol. 21, pp. 84–99 (2001). doi: [10.1109/37.898794](https://doi.org/10.1109/37.898794)
- [3] Sipahi, R., Niculescu, S., Abdallah, C. T., Michiels, W. and Gu, K., "Stability and Stabilization of Systems with Time Delay. Limitations and Opportunities," *IEEE Control Systems Magazine*, Vol. 31, Issue 1 (2011). doi: [10.1109/MCS.2010.939135](https://doi.org/10.1109/MCS.2010.939135)
- [4] Peng, C., Tian, Y. C. and Tade, M. O., "State Feedback Controller Design of Networked Control Systems with Interval Time-varying Delay and Nonlinearity," *International Journal of Robust and Nonlinear Control*, Vol. 18, No. 12, pp. 1285–1301 (2008). doi: [10.1002/rnc.1278](https://doi.org/10.1002/rnc.1278)
- [5] Montestruque, L. A. and Antsaklis, P., "Stability of Model-based Networked Control Systems with Time-varying Transmission Times," *IEEE Transactions on Automatic Control*, Vol. 49, pp. 1562–1572 (2004). doi: [10.1109/TAC.2004.834107](https://doi.org/10.1109/TAC.2004.834107)
- [6] Montestruque, L. A. and Antsaklis, P., "On the Model-Based Networked Control Systems," *Automatica*, Vol. 39, pp. 1837–1843 (2003). doi: [10.1016/S0005-1098\(03\)00186-9](https://doi.org/10.1016/S0005-1098(03)00186-9)
- [7] Chen, P.-C., The Study, Design and Realization of the Portable Unmanned Aerial Vehicle, Master Thesis, Tamkang University, June (2009).
- [8] Liao, S.-H., *Multi-chip Flight Computer of Unmanned Aerial Vehicle*, Master Thesis, Tamkang University, June (2010).
- [9] Chang, C.-M., Analysis and Design of a Model-Based Flight Control System with Time-Delay, Master Thesis, Tamkang University, June (2012).
- [10] Norris, R. B., A Distributed Flight Control System Architecture for Small UAVs, Master Thesis, Massachusetts Institute of Technology, USA (1998).
- [11] Palmintier, B., Twigg, R. and Kitts, C., "Distributed Computing on Emerald: A modular approach for Robust Distributed Space Systems," *2000 IEEE Aerospace Conference Proceedings*, Vol. 7, pp. 211–222 (2000). Bigsky, MT USA. doi: [10.1109/AERO.2000.879289](https://doi.org/10.1109/AERO.2000.879289)
- [12] Kitts, C. and Swartwout, M., "Autonomous Operations Experiments for the Distributed Emerald Nanosatellite Mission," *Proceedings of the AIAA/USU Conference on Small Satellites, Advanced Operations Concepts*, SSC-00-IX-5 (2000). <http://digitalcommons.usu.edu/smallsat/2000/All2000/>.
- [13] Palmintier, B., Kitts, C., Stang, P. and Swartwout, M., "A Distributed Computing Architecture for Small Satellite and Multi-Spacecraft Missions," *Proceedings of the AIAA/USU Conference on Small Satellites, Innovative Mission Operation Concepts*, SSC-02-IV-6 (2002). <http://digitalcommons.usu.edu/smallsat/2002/all2002/>.
- [14] Shiau, J.-K. and Hung, W.-S., "Development of a Distributed Multi-MCU Based Flight Control System for Unmanned Aerial Vehicle," AASRC Conference, Tainan, Nov. 15, 2114, Taiwan (2014).
- [15] Shiau, J.-K. and Wang, I.-C., "Unscented Kalman Filtering for Attitude Determination Using MEMS Sensors," *Journal of Applied Science and Engineering*, Vol. 16, No. 2, pp. 165–176 (2013). doi: [10.6180/jase.2013.16.2.08](https://doi.org/10.6180/jase.2013.16.2.08)

**Manuscript Received: Mar. 20, 2015**

**Accepted: Jul. 6, 2015**