Design and Tests of Guidance and Control Systems for Autonomous Flight of a Low-Speed Model Airplane for Application to a Small-Scale Unmanned Supersonic Airplane

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To realize innovative transportation systems for intercontinental flight and orbital spaceflight, it is essential to establish the necessary aerodynamic, structural, propulsion, and control technologies for a vehicle to fly at high altitudes and speeds within the atmosphere, and to verify them by using small-scale unmanned supersonic experimental aircraft. This paper describes the control technologies for a 3-kg low-speed model airplane flying autonomously from takeoff, through a circuit, to landing. Guidance and control systems are established for the plane, and flight experiments verify that the control laws work well for all flight modes.

Key Words: Autonomous, Guidance and Control, UAV, Low-Speed, Model Airplane, Supersonic, Experiment

Nomenclature

d	: deviation from reference
g	: gravitational acceleration
h	: height from ground
u	: x component of velocity in a body-fixed frame
V	: total velocity
γ	: flight path angle
δ	: angle of aileron, elevator, rudder
ϕ	: roll angle
θ	: pitch angle, glide slope angle
ψ	: heading angle
τ	: flare time constant

Subscripts

0	: initial or start
G	: glide slope
R	: rotation
a	: aileron
c	: command
e	: elevator
r	: rudder
s	: switching value
T	: throttling

1. Introduction

There is currently an increasing need for innovative transportation systems for both intercontinental flight and orbital spaceflight. To realize such systems, it is essential to establish aerodynamic, structural, propulsion, and control technologies to enable a vehicle to fly at high altitudes and high speeds within the atmosphere. The Aerospace Plane

Fig. 1. Flight verification by small-scale supersonic airplane.

Research Center (APReC) at the Muroran Institute of Technology in Japan is researching and developing such technologies, as well as constructing a small-scale unmanned supersonic experimental airplane called “Oowashi 2nd”, as a flying testbed. This final targeted airplane has a delta wing for supersonic flight, can cover distances in excess of several tens of kilometers, can reach a speed of Mach 2, and will be verified as shown in Fig. 1. The control technology for the airplane must not only fly the airplane fully autonomously but also be robust to uncertainties such as unexpected wind gusts and changes in vehicle dynamics caused by fuel consumption and un-modeled vibration.

To meet the above requirements, for Phase 1 of this project, we aim to establish the guidance, navigation, and control (GNC) systems for firstly a highly stable model airplane, then an intermediate airplane, and finally a supersonic experimental airplane. In Phase 1, our objective is to realize fully autonomous flight from takeoff, through a circuit, to landing.

Of the many studies of flight-control technologies for unmanned aerial vehicles (UAVs), only a few,^{1)–7)} have realized autonomous flight in flight experiments, and most of those were dedicated to a specific flight mode such as landing.

The aircraft used in those studies weighed roughly 50 kg,¹⁻³⁾ 800 kg,⁴⁾ 18 kg,⁵⁾ or less than 1 kg.^{6,7)} Furthermore, no detailed description was given of all the control laws necessary for fully autonomous flight from takeoff, through a circuit to landing.

Therefore, with the ultimate aim of flying a supersonic UAV that will weigh roughly 300 kg, we describe here all the fundamental control laws that are necessary for fully autonomous flight of a 3-kg low-speed model airplane. We have implemented all the necessary hardware, such as the control circuits, sensors, actuators, and wireless communication equipment, and we have verified the control system in flight experiments using the model airplane. In particular, the flight modes are very important for realizing fully autonomous flight from takeoff, through a circuit to landing. The methods for compensating for sensor alignment and adjusting servo trims are also important, and are practical issues that must be solved in advance.

This paper is organized as follows. Section 2 describes the design and configuration policy of the GNC system according to development phases, which start from the Phase 1. Section 3 describes the flight modes that are necessary for fully autonomous flight, the control systems corresponding to the profiles, and the hardware, including the model airplane. Section 4 presents the results of the flight experiments, and the paper is concluded in Section 5.

2. Design and Configuration Policy of the GNC System

To make steady progress toward realizing a supersonic UAV, we take steps to implement the required GNC system, verify both its functions and hardware, and confirm its performance by successively upgrading the aircraft used in the flight experiments. We begin with a small model airplane, and will then progress to a large model airplane, a 1/3 scale subsonic UAV, and finally a small-scale supersonic UAV. These steps are defined as Phases 1–4, respectively. Phase 1 is focused on establishing all the necessary control laws for fully autonomous flight of a stable low-speed model airplane. Phase 2 involves a stable moderate-speed model airplane, and is focused on improving the control performance, adding functions to assign waypoints, and allowing the airplane to return to base in case of an emergency. Phase 3 is focused on

realizing control laws for an unstable subsonic airplane that is a one-third-scale version of the second-generation small-scale supersonic airplane “Oowashi”. Phase 4 is focused on realizing fully autonomous supersonic flight with all necessary functions. The objectives of each phase are summarized in Table 1, along with the required functions and associated performance. Based on these, hardware such as sensors and wireless communication equipment are prepared. The required functions, performance, and hardware are described in Sections 2.1 and 2.2. Conceptual images of the aircraft used as flying testbeds of the control system are shown in Fig. 2.

Fig. 2. Conceptual images of airplanes used as flying testbed.

2.1. Functions and performance

To realize autonomous flight, it is necessary for the UAV to be equipped with the functions and performance described in Table 1. Initially, the UAV is required to fly autonomously only from takeoff to landing. However, in the next phase, the heavier aircraft must land with a descent rate as low as possible. Also, from the viewpoint of safety, it must fly over a set of designated waypoints on an accurate flight path, and return to its takeoff mark or a designated location in the event of an emergency or abort in the worst case. The waypoints are assigned before the flight and could be changed inflight. These functions should be managed by a flight computer.

2.2. Hardware

Table 2. Hardware corresponding to airplane migration.

	Type	Phase 1	Phase 2	Phase 3	Phase 4
		Model airplane	1/3 scale	Full scale	
Air Plane	Power	Electric motor	Fuel engine	EDF/Jet engine	GG-ATR
	Length (m)	1.4	1.6–2.0	2.0	6.0
	Span (m)	1.6	1.8–2.0	0.8	2.4
	Wing form	Rectangle	Rectangle	Delta	Delta
	Weight (kg)	3	6	10	300
GNC System	Circuit	Minimum I/F	Full I/F	Full I/F	Full I/F
	Sensors	Prototype	Prototype	Prototype	Improved
	Actuators	Low torque	Medium torque	Large torque	Large torque
	Comm. module.	Short distance, low transmission capacity	Medium distance, large transmission capacity	Long distance, large transmission capacity	Long distance, large transmission capacity

Table 1. Objectives, functions, and performance for each phase.

Phase	Objectives of control system	Flight control		Flight management	
		Autonomous flight	Required descent rate & path accuracy	Waypoint assignment	Safety mode
1	Control law for a stable low-speed airplane	Full	Low	N/A	N/A
2	High performances and functions for a stable and medium-speed airplane	Full	Moderate	In advance	Go-home
3	Control law for an unstable subsonic speed airplane	Full	High	Changeable during flight	Go-home/Abort
4	High performances and functions for an unstable supersonic airplane	Full	High	Changeable during flight	Go-home/Abort

To achieve the objectives defined for each phase, the hardware for the control system is replaced or upgraded according to the schedule given in Table 2. Initially, model airplanes are used to confirm the functions and performance of the GNC system. It is then improved and updated for application to the targeted supersonic UAV by either upgrading or replacing the circuit, sensors, actuators, and communication modules in Phase 1 of the GNC system. The sensors must be replaced to cope with the increased flight speeds and altitudes. The actuators—especially the servomotors for the ailerons, elevator, and rudder—have to be replaced with ones that can generate more torque according to the aircraft used. Other than the GNC circuit, commercially available hardware is used.

3. Guidance and Control Systems for Model Airplane

3.1. Flight mode and control systems

For an airplane to fly fully autonomously, we must design control laws for both longitudinal and lateral directional motion. The aim is to achieve target values for state variables such as position, speed, and attitude, and to use them in the corresponding flight mode (i.e., takeoff, a circuit, or landing). Table 3 lists the flight modes prepared for the motor-driven model airplane. Each flight mode is achieved by using multiple fundamental control systems. Detailed control systems for each flight mode are described in the following subsections. In all flight modes, the roll angle is kept constant at the required value.

Table 3. Flight mode and required control system.

Flight mode	Kinds of control system
Takeoff	Running control
	Rotation control
	Climb control
	Lateral directional position control
Circuit	Roll control
	Height control
	Speed control
	Heading control
	Glide slope and speed control
Landing	Flare control
	Roll-off control
	Lateral directional position control

3.1.1. Takeoff flight

A takeoff flight-control system consists of three elements, namely, running control, rotation control, and climb control. These are used according to the takeoff profile,^{8,9)} as shown in

Fig. 3. Takeoff profile.

Fig. 3. During the takeoff run, the running-control system maintains direction down the runway as the aircraft accelerates to its rotation speed V_R . The heading is controlled mainly by steering while on the runway and by the rudder once airborne. Upon reaching V_R , the rotation-control system effects a nose-up attitude, increasing the angle of attack and therefore increasing the lift force. This causes the aircraft to rise into the air and continue to climb, accelerating to the safe speed V_2 for takeoff that is specified for a height of 10 ft. Upon reaching V_2 , the aircraft continues its climb to 400 ft at the same speed. The climb-control system maintains the speed at V_2 by using the pitch controller because the aircraft is climbing at maximum thrust. A block diagram of the takeoff-control system is shown in Fig. 4.

Fig. 4. Block diagram of takeoff control.

3.1.2. Circuit flight

A circuit flight requires two control systems, namely, cruise control and turn control. These are used according to the circuit-flight profile as shown in Fig. 5. The control system changes the flight mode from cruise control to turn control

Fig. 5. Circuit-flight profile.

Fig. 6. Block diagram of circuit-flight control.

when the aircraft passes a designated point or has flown for a specified time. Once the aircraft has turned onto a specified heading, the control system changes the control mode back to cruise control. During both level flight and turning, the roll angle, height, and speed are controlled to maintain their designated predetermined values. The pitch controller is responsible for the height. If the height decreases, the pitch controller compensates by increasing the pitch angle, causing the aircraft to ascend; if the height increases, the pitch controller decreases the pitch angle, causing the aircraft to descend. A block diagram of the control systems for a circuit is shown in Fig. 6; unlike takeoff control, speed and height are controlled independently.

3.1.3. Landing

Landing consists of four control systems, namely, glide-slope control, flare control, speed control, and lateral directional-position control. These are used according to the landing profile,^{10, 11)} as shown in Fig. 7. The objective is to keep the aircraft descending at constant speed on a constant glide slope, contrary to effects of gravity. When the aircraft reaches the height h_0 —the height at which flare control commences, as determined by a flare time constant and the descent rate of the glide slope—the descent rate is controlled so that it is proportional to height, allowing the aircraft to touch down on the runway without severe impact. To realize this, flare control is based on height as measured by a pressure altimeter, with bias compensated by an ultrasonic sensor at the start height for flare control. After touchdown, the aircraft is controlled while moving forward. A block diagram of the landing-control system,¹²⁾ is shown in Fig. 8.

Fig. 7. Landing profile.

Fig. 8. Block diagram of landing control.

3.2. Hardware configurations of model airplanes and GNC system

3.2.1. Model airplane

Figure 9 shows the model airplane used in Phase 1; its main

parameters are listed in Table 4. It is propelled by an electric motor and can fly at a maximum speed of 80 km/h.

Fig. 9. Model airplane for flight experiments.

Table 4. Major parameters of model airplane.

Total weight with all onboard equipment	[kg]	3
Wing area	[m ²]	0.364
Wing span	[m]	1.6
Full length	[m]	1.4
Mean aerodynamic chord	[m]	0.25
Inertia moment about pitch axis	[kg m ²]	0.132

3.2.2. GNC system

The GNC system shown in Figs. 4, 6, and 8 is configured for the model airplane as shown in Fig. 10. The system consists fundamentally of a GNC circuit, sensors, actuators, and wireless communication modules with their performances shown in Table 5. The sensors are a pressure sensor, an ultrasonic sensor, and a hybrid Inertial Navigation System (INS). The former two sensors measure height, the latter

Fig. 10. Hardware of guidance and control system.

Table 5. Performance of sensors and wireless module.

Hybrid INS/GPS equipment	Update time	40 ms
	Position accuracy	3 m (rms)
	Velocity accuracy	0.3 m/s (rms)
	Pitch/roll accuracy	0.5° (rms)
	Heading accuracy	3° (rms)
Height sensor	Weight	50 g
	Pressure sensor Accuracy	0.2 m
	Ultrasonic sensor Update time	10 ms
	Ultrasonic sensor Accuracy	0.01 m
Wireless module	Update time	100 ms
	Frequency band	2.4 GHz
	Information transmission speed	19.2 kbps

measures position, velocity, attitude (roll, pitch, and yaw), and angular velocity, with GPS for compensation. The system includes a telemetry system that uses wireless communication modules. The flight of the model airplane is switched between manual and automatic control by a radio controller known as “Propo.” The GNC circuit is the only trial product; all other hardware is ready made. The circuit calculates the control law based on the data derived from sensors every 40ms, which is the update time of the INS.

4. Design and Flight Experiment of Model Airplane

4.1. Control system design

Firstly, the aerodynamic coefficients,¹³⁾ for both the longitudinal and lateral directional dynamics of the model airplane are calculated according to the size of the airplane. The control laws for each flight mode are then designed based on those coefficients. The control laws consist mainly of proportional, integral, and derivative (PID) elements. The values of those elements are determined based on classical control theory by using a Bode diagram to achieve at least a gain margin of 10 dB and a phase margin of 30°. The designed control bandwidths, 3 dB down frequencies from the peak gain of the closed loop transfer function of the control system in the Gain Bode diagram, for each flight mode are summarized in Table 6. The larger the bandwidth becomes, the more responsive the control system is.

Table 6. Designed control bandwidths.

Flight mode	Control-system type	Control bandwidth
Takeoff	Running control	0.16 Hz
	Rotation control	0.44 Hz
	Climb control	0.44 Hz
	Lateral directional position control	0.03 Hz
Circuit	Roll control	0.10 Hz
	Height control	7.65 Hz
	Speed control	0.30 Hz
	Heading control	0.67 Hz
Landing	Glide slope control	0.06 Hz
	Speed control	0.27 Hz
	Lateral directional position control	0.16 Hz
	Flare control	0.12 Hz
	Roll-off control	0.27 Hz

4.2. Adjustment of sensor misalignment and servo trim

There is usually some misalignment between the body-fixed and sensor-fixed coordinates, resulting in attitude biases. The extent of this misalignment can be measured to a certain degree by flying the airplane horizontally along the x direction in the body-fixed frame, although it is necessary and difficult to confirm whether the airplane flies horizontally. By this method, the bias angles of roll, pitch, and yaw were measured and compensated for during the flight, although the extent to which those biases were eliminated is unsure. When the airplane flies straight and level without manual operation of Propo, the positions of the servomotors that drive the ailerons, elevator, and rudder can be regarded as being in a neutral state known as “trim.” The servomotors should be adjusted so that they are in the neutral positions when the command by controllers is zero; this means that the zero command should coincide with the neutral positions of the

servomotors. This can be also realized by adjusting the lengths of the linkages that connect the servomotors and the control surfaces (i.e., the ailerons, elevator, and rudder).

4.3. Flight experiments

Flight experiments for the flight modes specified in Table 3 were carried out at the Shiraoi gliding port in Hokkaido, Japan, to assess their validity and confirm the flight performance with the hardware described in Section 3.2. Detailed flight results are described below.

4.3.1. Takeoff flight

Figure 11 shows the trajectory of the takeoff flight. A red line indicates that the airplane was flying autonomously; a white line indicates that it was being flown manually. The data for pressure height and lateral directional position are shown in Fig. 12. The flight trajectory and data confirm that the airplane ran smoothly, rotated its nose, and climbed to a height of 84.6 m, the horizontal distance of which was the visible limit. The speed increased smoothly to 18 m/s in 5 s, and was held constant within a deviation of ± 2 m/s. The aircraft deviated laterally from the center line of the gliding port by a maximum distance of 33.3 m, but eventually returned to center. After investigating the flight, this deviation

Fig. 11. Trajectory of takeoff flight.

(a) Height

(b) Lateral directional position

Fig. 12. Flight data of takeoff.

was found to have been caused by an abnormal output of the heading angle from the hybrid INS/GPS; it took too long for the INS/GPS to converge the angle to an accurate value for climbing. Though dependent on causes to be clarified from now on, a practicable solution to this problem might be to calculate the heading angle during takeoff via quaternions using angular velocities measured by an inertial measurement unit. Nevertheless, this test flight confirmed that the takeoff-control system worked satisfactorily.

4.3.2. Circuit flight

Figure 13 shows the trajectory of the circuit flight. Red and white lines indicate the airplane flying autonomously or under manual control, respectively. The data for pressure height and

Fig. 13. Trajectory of circuit flight.

roll angle are shown in Fig. 14, where “L” means level flight and “T” means a turn. The flight trajectory and data confirm that the airplane remained reasonably level both when flying straight and turning. The airplane completed three circuits covering a distance of 700 m each. This test flight confirmed that the circuit-flight control system worked satisfactorily.

(a) Height

(b) Roll angle

Fig. 14. Flight data of circuit.

4.3.3. Landing

Figure 15 shows the trajectory of the landing. Red and white lines indicate the airplane flying autonomously or under manual control, respectively. The data for pressure height, descent rate, and lateral directional position are shown in Fig. 16. The flight trajectory and data confirm that the airplane descended along the glide slope with a deviation of 5 m, touched down on the runway with an average descent rate of 0.8 m/s, and deviated laterally by 2 m from the center line of the runway. This test flight confirmed that the landing-control system worked satisfactorily.

Fig. 15. Trajectory of landing flight.

(a) Height

(b) Descent rate

(c) Lateral directional position

Fig. 16. Flight data of landing.

5. Conclusion

With the ultimate aim of establishing control technologies for flying a supersonic UAV, we have designed fundamental

control laws necessary for fully autonomous flight of a 3-kg model airplane. Hardware such as a control circuit, sensors, actuators, and wireless communication modules were created, and their control performances were verified successfully in flight experiments. From these, we confirmed that 1) the takeoff-control system worked well despite an issue with the lateral directional position caused by the heading output of the INS/GPS, 2) the circuit-flight control system worked well despite a slight trajectory deviation, and 3) the landing-control system worked very well, with a position deviation of 2–5 m and a descent rate of 0.8 m/s. Our next goal is to rectify the aforementioned problems, improve the control performance and carry out successive fully autonomous flight from takeoff to landing for the UAV, and then to develop and verify a GNC system for a 1/3 scale unmanned supersonic vehicle.

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