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Research of Cargo UAV for Civil Transportation

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***Abstract*—**Our Cargo unmanned air vehicle (CARGO UAV) research had been started from 2004 in AIST. First flight of the CARGO UAV prototype was successfully achieved on November 22, 2005. The CARGO UAV prototype consists of flexible wing, twin micro turbo jet engine and a pendulum gravity center control unit. It has touchable safety (without any propellers or rotors), low stall speed less than 30 km/h, and silent turbojet engines for the thrust generator. These safety properties lead CARGO UAV possible to access to our living place. The CARGO UAV will be promising for civil logistics when the air road network for CARGO UAV is constructed for the future.

***Keywords*—** UAV, cargo, air transportation.

I. INTRODUCTION

UAV (unmanned air vehicle) is already available in military section for surveillance, reconnaissance, and assault operations, and under development for cargo and passenger transport for the next. Cargo and passenger transportation section of industry is as large as 10 % of gross national product as shown in **Figure 1**. Ninety percent of cargo and passenger transportation is carried out by automobiles nowadays as shown in **Figure 2**. The CARGO UAV operation has enough capability to bypass the automobile transport for the future and to create large market.

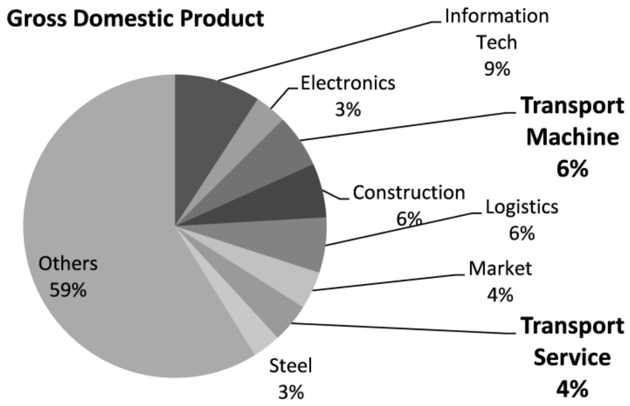

Figure 1 Transport section ratio in Gross domestic product

CARGO UAV operation needs wireless mesh network and service provider that is similar to cell phone network as shown in **Figure 3**.

The cell phone markets have rapidly become larger than that of public fixed-line network. The CARGO UAV transport network also has distributed ground port like a cell phone infrastructure. So, it will be able to be like a cell phone market and industry.

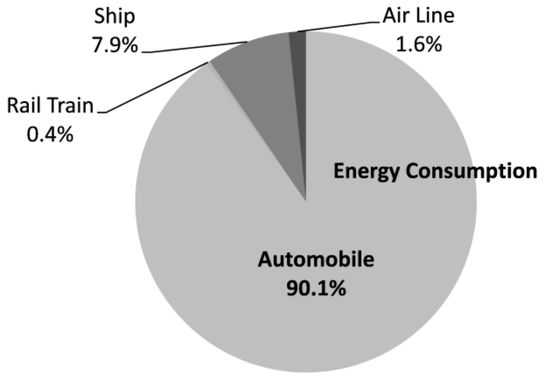

Figure 2 Energy consumption ratio of each transportation system

CARGO UAV transportation system makes hub-spoke transport style to random point-to-point traffic. The travel speed of CARGO UAV should be much slower compared with present airline transporters because CARGO UAV will make busy access to the surface ground for service. Comparison between trains and automobile are similar to that between airline business and CARGO UAV operation. This slow traveling speed is most important and makes a CARGO UAV useful and convenient like an automobile [1].

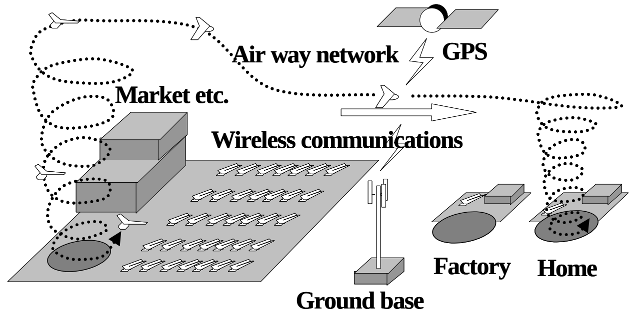

Figure 3 Concept of the CARGO UAV transportation system

Figure 3 shows a matured CARGO UAV system image in the future. This system consists of slow speed CARGO UAV and circle ports on ground that are able to take-off and landing with spiral sequence. Low speed flight around 100 km/h is important for safety and for keeping accessibility to the ground.

This kind of CARGO UAV will be used near by a social life space of human and should have certain durability, reliability, and safety. Reliable attitude control is quite important for safety operation of CARGO UAV. So, we have proposed an

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autonomous pendulum stability attitude control system for CARGO UAV [2].

II. PENDULUM ATTITUDE CONTROL OF THE CARGO UAV

In order to investigate a CARGO UAV system, a pendulum stabilized air vehicle structure is used, as shown in **Figure 4**. **Figure 4** shows a structure and a pendulum attitude stability method of the CARGO UAV, which enable to absorb shocks by gusts. Wing weight of the CARGO UAV must be as light as possible in order to put the center of gravity (CG) lower to acquire pendulum effects. The pendulum and a parachute structure provide intrinsic safety. An autonomous attitude control provides functional safety. Both lead CARGO UAV safe. A fabric-covered wing is suitable for a wing of the CARGO UAV. The wing is made of CFRP or duralumin frames and covered by synthetic fiber textile, and it can be folded easily during parking on the ground.

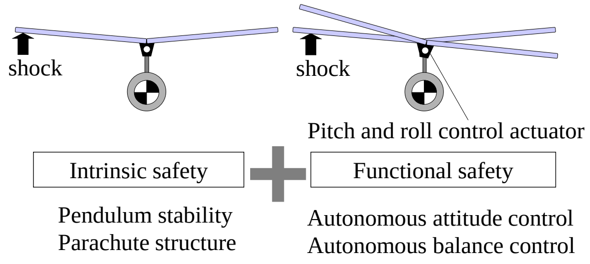

Figure 4 Both Intrinsic and Functional safety

The lightweight flexible wing is connected to the hull at a single point near the center of MAC (mean aerodynamic chord) with an actuator-controlled joint. Reducing stall velocity and attitude controllability at slow flight speed could be respectively attained by small wing loading and the CG control method. The actuator-controlled joint driven by roll- and pitch-axis servomotors can shift CG and steer the CARGO UAV.

This CARGO UAV structure makes its design work easy and simple. Only by measuring L/D (lift/drag) ratios of the wing and drag of the hull, the required thrust of CARGO UAV could be calculated.

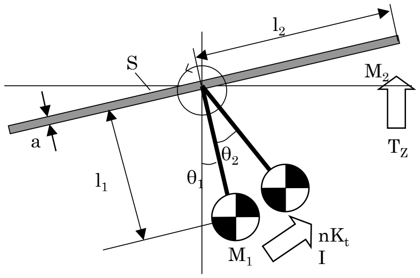

Figure 5 Pendulum attitude control motion model of roll movement

Figure 5 shows roll movement motion model for a dynamic inversion pendulum attitude control of the CARGO UAV. Motion equations of roll movement (CCW is positive) are following:

$$\left[M_1 l_1^2+\frac{1}{12}M_2(l_2^2+a^2)\right]\frac{d^2\theta_1}{dt^2}+\frac{1}{4}C_D S\rho\theta_1^2\cos\left(\frac{d\theta_1}{dt}\right) \quad (1)$$
$$-M_1 g\sin\theta_1=T_z$$

$$M_1 l_1^2\frac{d^2\theta_2}{dt^2}+\frac{1}{12}M_2(l_2^2+a^2)\frac{d^2\theta_1}{dt^2}$$
$$+\frac{1}{4}C_D S\rho\theta_1^2\cos\left(\frac{d\theta_1}{dt}\right)-M_1 g\sin(\theta_1+\theta_2)=nK_t I \quad (2)$$

where, I is motor current [A], a is wing thickness [m], g is gravity acceleration [m/s^2], M_1 is mass of the body [kg], M_2 is mass of the wing [kg], J_1 is moment of inertia of the body [kgm^2], J_2 is moment of inertia of the wing [kgm^2], l_1 is length of between the body and wing [m], l_2 is half length of wing span [m], K_t is torque constant of the motor [Nm/A], n is reduction ratio of the gear, ρ is density of standard atmosphere [kg/m^3], C_D is drag coefficient [m/s^2] and S is area of the wing [m^2].

Disturbance T_z usually takes 2~3 m/s of average and is small compared with air speed. So, θ_1 is small enough and approximations of $\theta_1\approx 0$, $\sin\theta_1\approx\theta_1$, $\cos\theta_1\approx 1$ are able to induce.

$$\frac{dx}{dt}=Ax+bI \quad (3)$$

where

$$x=\begin{bmatrix}\theta_1\\ \theta_2\\ \dot\theta_1\\ \dot\theta_2\end{bmatrix},\quad A=\begin{bmatrix}0&0&1&0\\0&0&0&1\\a_1&0&0&0\\a_2&a_3&0&0\end{bmatrix},\quad b=\begin{bmatrix}0\\0\\b_1\\b_2\end{bmatrix},$$

Element a_1~a_3, b_1, b_2 are led as following using (1) and (2).

$$A_0\begin{bmatrix}\ddot\theta_1\\ \ddot\theta_2\end{bmatrix}+B_0\begin{bmatrix}\theta_1\\ \theta_2\end{bmatrix}+C_0\begin{bmatrix}\dot\theta_1^2\\ \dot\theta_2^2\end{bmatrix}=D_0 I \quad (4)$$

where

$$A_0=\begin{bmatrix}M_1 l_1^2+\frac{1}{12}M_2(l_2^2+a^2) & 0\\ \frac{1}{12}M_2(l_2^2+a^2) & M_1 l_1^2\end{bmatrix}$$

$$B_0=\begin{bmatrix}M_1 g&0\\M_1 g&M_1 g\end{bmatrix}\quad C_0=\begin{bmatrix}\frac{1}{4}C_D S\rho&0\\ \frac{1}{4}C_D S\rho&0\end{bmatrix}\quad D_0=\begin{bmatrix}-nK_t\\ nK_t\end{bmatrix}$$

Dynamic inversion pendulum attitude control of the CARGO UAV was carried out using (4) by 2-axes actuator as shown in **Figure 6**. The torque of the 2-axes actuator is as large as about 250 kgm because the wing span (twice of l_2 in **Figure 5**) is as large as 10 m. The 2-axes actuator moves wing itself directory for pitch and roll control of the CARGO UAV.

The flight track of CARGO UAV becomes summation of arcs of many circles as shown in **Figure 7**. The radius R_n of the circle in **Figure 7** is given as following:

$$R_n=\frac{2(M_1+M_2)}{C_L S\sin\theta_n} \quad (5)$$

where C_L is lift coefficient, S is wing area.

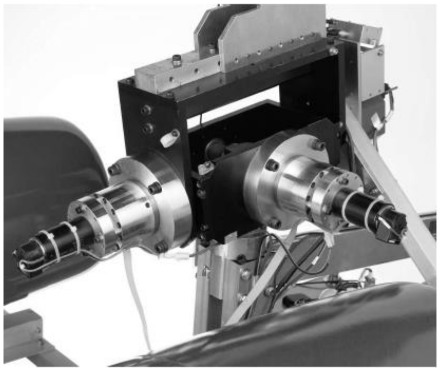

Figure 6 Photograph of the 2-axes actuator of CARGO UAV

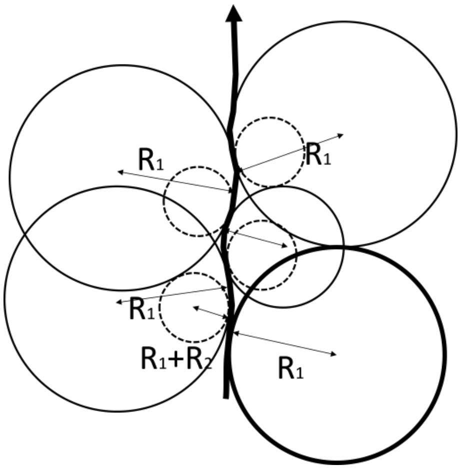

Figure 7 The flight track of CARGO UAV

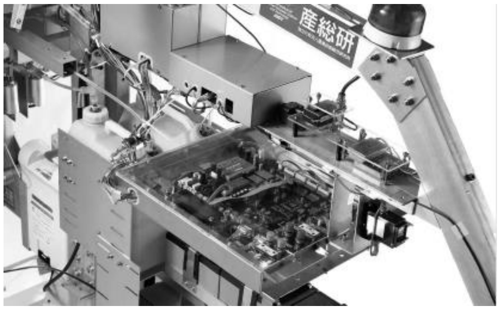

Figure 8 Photograph of the 2-axes actuator of CARGO UAV

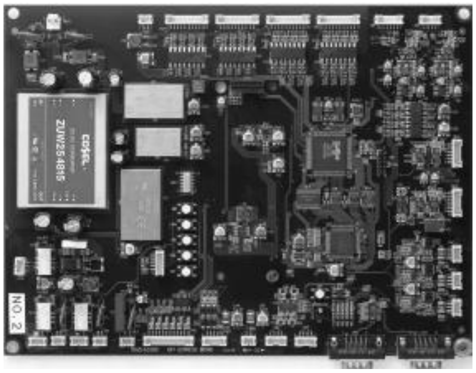

Figure 9 Photograph of the 2-axes actuator of CARGO UAV

The 2-axes actuator is controlled by microcomputer controller as shown in **Figure 8** and **Figure 9**. Electrical equipment is floated to the frame of the CARGO UAV. All the signal lines are isolated by photo coupler as can be seen in **Figure 9**.

CARGO UAV prototype was constructed and has an optimized body structure in strength with reinforced suspensions and actuators. Large wing area of 18.1 m^2 is required to carry a 50 kg of payload for small cargo transportation. **Figure 10** shows a left-rear view of the CARGO UAV prototype. Fuel tanks are located at the center of the dangling body in order to keep its balance during flight as shown in **Figure 4**. Two lithium-ion batteries are equipped as an energy source for roll- and pitch-actuators and as ballast. The batteries are mounted on a bottom frame bone of the CARGO UAV prototype and their weight makes the center of gravity (CG) of the CARGO UAV prototype lower.

The CARGO UAV prototype is steered by shifting its gravity center like a pendulum using the roll- and pitch actuator. A dangling body of the CARGO UAV prototype acted as a weight of a pendulum and needs some suitable volume in order to keep safety stability.

Figure 10 Left rear view of CARGO UAV prototype

A spread foldable wing is jointed to the dangling body frame through a single point near the center of Mean Aerodynamic Chord (MAC). The joint between the wing and the dangling body frame of the CARGO UAV prototype consists of roll- and pitch-actuators. Twin silent turbojet engines are mounted on the upper dangling body. This thrust point is important to stabilize pitch attitudes of the CARGO UAV prototype.

A suspension system consisted of twin coils and dampers are quite effective for landing shock reduction. Damping rate can be arbitrary chosen depending on runway conditions.

Steering of the front wheel is necessary to keep straight direction on a runway for take-off. The main computer mounted on the center of the dangling body controls vehicle attitude automatically by driving the actuated joint. Commands from the operator are transmitted to the main computer through the radio signal receiver as shown in **Figure 11**.

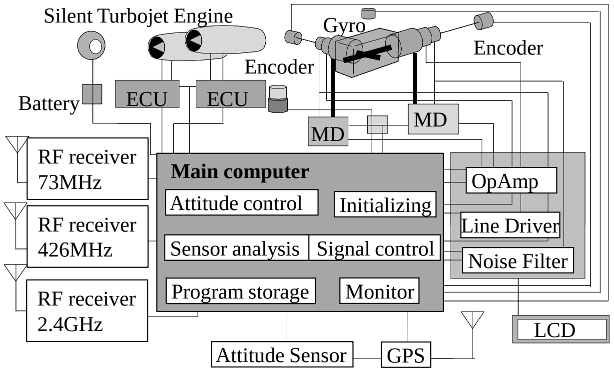

Figure 11 The control system of CARGO UAV prototype

III. FLIGHT TEST OF THE CARGO UAV

Flight experiments were conducted in order to measure take-off speeds and distances, and check the corresponding thrusts. On November 22 in 2005, the CARGO UAV prototype made its successful first flight.

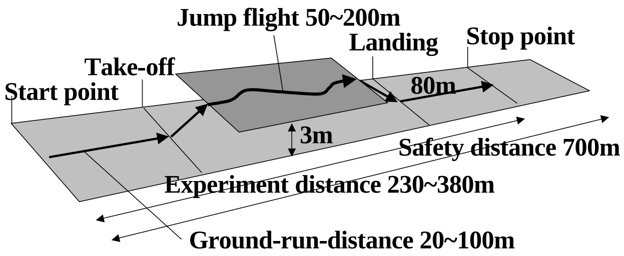

Figure 12 Test course of flight experiment of CARGO UAV

Figure 12 shows the flight test course of the CARGO UAV prototype. All the test flight was carried out as low altitudes as about 3 m for safety. **Figure 13** shows a scene to minimize ground-run-distance for take-off. We have accomplished the distance reduction up to 36 m in 2006. The take-off speed was 32.4 km/h (9.0 m/s) and the wing attack angle was 16 degrees. The attack angle should be adequately controlled by the pitch-actuator because the angle varies according to turbojet thrust levels, location of CG, and airspeed of the CARGO UAV prototype.

Figure 13 Flight test of the CARGO UAV prototype

The measured flight speed of 32.4 km/h and take-off distance of 36 m are enough slow and short to realize the transport system in **Figure 3**.

IV. SMALL CARGO UAV FOR AUTO BALANCE CONTROL

The CARGO UAV prototype in **Figure 10** and **Figure 13** is too large to study the pendulum attitude balance control. So, we designed a small CARGO UAV by 3D-CAD as shown in **Figure 14**. **Table 1** shows scale comparison of the CARGO UAV prototype and the small CARGO UAV. The Small CARGO UAV has 1/3 scale of CARGO UAV prototype in **Figure 10** and **Figure 13**. The frame indicated in **Figure 15** was designed as having sweepback angle: 60 degree, dihedral angle: 10 degree, and wash-out angle: 5 degree. The length, radius and thickness of the spar frame in **Figure 15** are determined by elastic deformation and stress analysis as shown in **Figure 16** and **Figure 17**.

Table 1 Size of small CARGO UAV

	CARGO UAV Prototype	Small CARGO UAV
Wing span	**10 m**	**3 m**
Wing area	**19.5 m^2**	**2 m^2**
Weight	**100 kg**	**3 kg**
Thrust	**50 kgf**	**1.5 kgf**

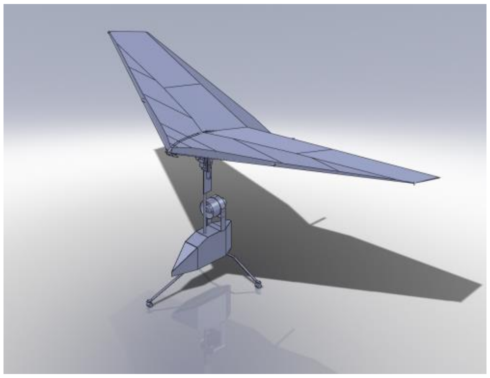

Figure 14 3D-CAD design of small CARGO UAV

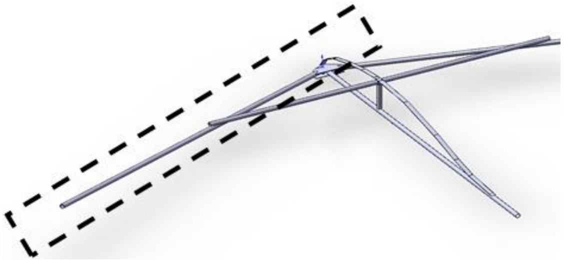

Figure 15 The spar frame of Small CARGO UAV

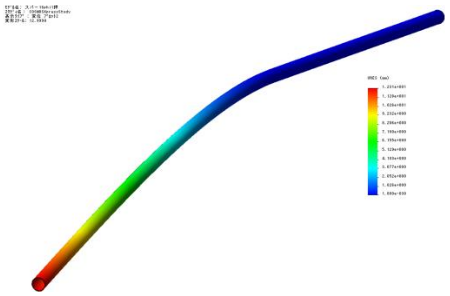

Figure 16 Elastic deformation analysis of the spar frame of Small CARGO UAV

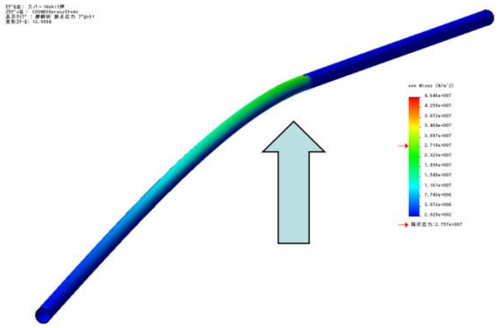

Figure 17 Strain analysis of the spar frame of Small CARGO UAV

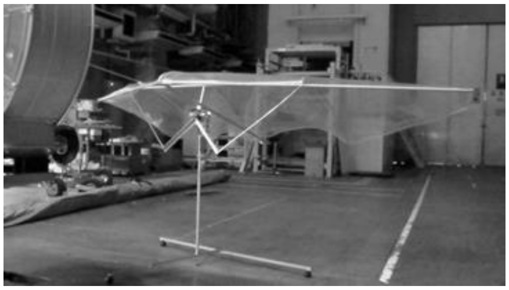

Figure 18 Front view of experimental Small CARGO UAV

Figure 19 Starting location of the attitude control experiment

Figure 20 Without attitude control at 7 seconds after start

Figure 21 With attitude control since 1 hour

Figure 18 shows the experimental Small CARGO UAV for attitude control study. Small 2-axes actuator is located under the center of the wing. Air turbulence is generated by three electrical fans which has as large diameter as 90 cm as shown in **Figure 19**. **Figure 19** also indicates the starting location of experimental Small CARGO UAV. In the case without attitude control, the Small CARGO UAV swerved out to right-hand side in 17 seconds after an experiment start as shown in **Figure 20**. However, in the case with attitude control, the Small CARGO UAV kept horizontal attitude. **Figure 21** shows the stable attitude of Small CARGO UAV since 1 hour after an experiment start, and it continued maintaining a posture still more. This is the excellent feature of this flight object and can rectify the unbalance of manufacture by attitude control.

V. CONCLUSION

The concept and design criteria of CARGO UAV system for transportation and logistics were proposed. The first flight was successfully made on November 22, 2005. The experimental small CARGO UAV indicated the enough stability of attitude and excellent feature that the CARGO UAV can rectify the unbalance of manufacture by attitude control. CARGO UAV will open large commercial and civil markets for air transportation when an air road network for CARGO UAV is constructed in the future.

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