AIAA <i>Infotech@Aerospace</i> 2007 Conference and Exhibit
7-10 May 2007, Rohnert Park, California

AIAA 2007-2784

UAV for Small Cargo Transportation

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[Abstract] The status quo of a research on a novel UAV (Un-manned Air Vehicle) transportation system is presented. Under a new concept for a short haul aerial transportation system, three-Dimensional Transportation Robots (3DTR) were constructed with twin turbojet engines equipped by high performance noise reduction system and a flexibly jointed delta wing controlled by 2-axis actuators. This vehicle is also suitable for aerial surveillance. The maiden flight was successfully conducted on November 22, 2005.

I. Introduction

Table 1. Comparison between typical public and personal transportation systems

Item	Surface		Air	
	Public	Personal	Public	Personal
Vehicle Type	Train	Automobile	Air line	3DTR
Door to Door	Unable	Able	Unable	Able
Speed	Fast	Slow	Fast	Slow
No. of Passengers	Many	Few	Many	Few
Life Time	Long	Short	Long	Short
Vehicle Price	High	Low	High	Low
Production Mass	Few	Many	Few	Many
Industrial Scale	Smaller	Larger	Smaller	Larger

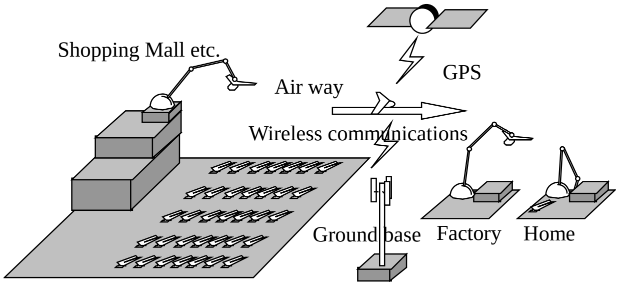

Figure 1. Concept of a novel personal air transportation system.

THIS research is a challenge for creation of a novel personal transportation system. Transportation is indispensable not only for various industry sectors but also daily personal life. Transportation systems can be classified into two types, public and personal ones as shown in Table 1. The Important point is differences of production scales. Markets for personal uses have become larger than that for public uses in history, because the former ones match mass production. Progresses in transportation systems have been made from hub-spoke styles to random point-to-point traffics. However, in the air, personal vehicles are not yet freely available. This is why we are trying to develop a newly conceived 3-dimensional-transportation robot (3DTR).[1] UAV for small cargo transportation is one application of 3DTR. Table 1 indicates that the travel speed of 3DTR could be much slower compared with airline transporters. This is analogous to a comparison between train and automobile as shown in Table 1. This difference of traveling speed is most important and makes the starting point of this research. Figure 1 shows a matured 3DTR system image in the future. This system consists of slow speed 3DTRs and high-speed ground-based manipulation robots that are able to catch and launch 3DTRs. Technological realizations of slow speed 3DTR and high-speed manipulation of ground-based take-off and landing aid robots bring this system real. This kind of a large ground-based manipulation robot is commercially available by a Japanese foremost machine builder (Fig.2). This machine can swing its arm tip up to

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40km/h. Its speed is high enough to catch a 3DTR at a flight speed of 30km/h. So, the first objectives of this research are to make a 3DTR fly safely at this slow speed.

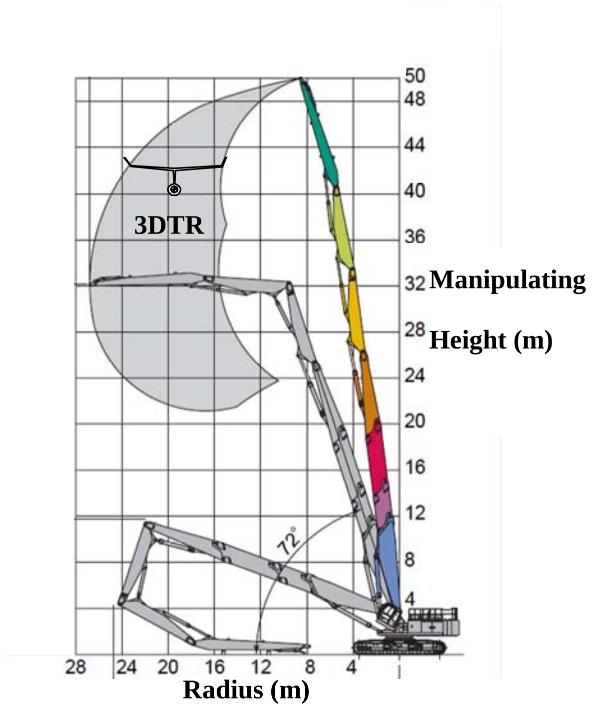

Figure 2. A high-speed ground-based manipulation robot.

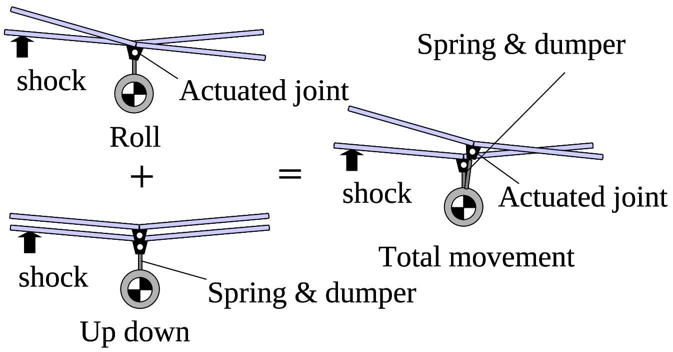

Figure 3. The basic structure of 3DTR.

II. Configurations of 3DTR

A. Concept and basic design

Stability in slow flights is indispensable for a 3DTR, and at the same time gust alleviation features are required. Figure 3 shows a structure and a pendulum attitude stability method of 3DTR, which enable to absorb both rotational and translation shocks by gusts.

A wing weight of 3DTR must be as light as possible in order to position the center of gravity (CG) lower to acquire pendulum effects. A fabric-covered wing is suitable for a wing of 3DTR. The wing is made of CFRP or duralumin frames and covered by synthetic fiber textile, then it can be folded easily during parking on the ground as shown in Fig.4. 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 3DTR.

This 3DTR 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 3DTR could be calculated as shown in Fig.5.

Required thrusts are given by measured L/D values as the following;

$$D = C_D \frac{1}{2} \rho \boldsymbol{v}^2 S = T_r \qquad (1)$$

$$L = C_L \frac{1}{2} \rho \boldsymbol{v}^2 S = W \qquad (2)$$

where D, L, T_r, W, ρ, v, S, C_D and C_L are, respectively, drag, lift, required thrust, vehicle weight, air density of ISA (International Standard Atmosphere), velocity, wing area, drag coefficient and lift coefficient.

Using Eq.(1) and (2), T_r can be written as

$$\begin{aligned} T_r &= \frac{W}{C_L / C_D} = \frac{C_{D\min}}{C_L} W + \frac{C_L}{\pi e A} W \\ &= \frac{C_{D\min} S \rho}{2} \bullet \boldsymbol{v}^2 + \frac{2W^2}{\pi e A S \rho} \bullet \frac{1}{\boldsymbol{v}^2} \end{aligned} \qquad (3)$$

where A, e, and C_{Dmin} are aspect ratio, airplane efficiency and minimum parasitic drag coefficient. C_{Dmin} is defined by

$$C_D = C_{D\min} + \frac{C_L^2}{\pi e A} \tag{4}$$

Required thrust curves in Fig.5 consist of function of v^2 as shown in Eq.(3) [3].

Required thrust curves for three types of wings are plotted in Fig.5. The wings of F195 and US147 have Duralumin frames and EXT160 has CFRP frames. 3DTR can have different specifications simply by changing its wing type.

B. Turbojet Engine of 3DTR

Thrust generation systems with bare propeller blades are not suitable for this kind of robots because of considerably large sizes of hazardous rotational bladed thrusters whose diameters are estimated as about 1350mm for the present 3DTR. Safety is one of the most important features of robots. So, we have chosen turbo jet engines as thrusters for 3DTR. A modern jet engine has advantages as the following; protection against possible injury, little vibration, space saving, lightweight due to high thrust per weight ratio and reliability. Recent innovation of turbo jet engines has achieved high thrust per weight ratio of up to 6 and is able to reduce thruster weight to 8kg at maximum thrust of 47kgf.

However, a turbojet engine has a serious problem of large acoustic emission. We measured a purchased turbojet engine noise and obtain an unbearable noise level of 110dB. So, we have invented a silencer of the turbojet engine. Figure 6 shows the structure of the quiet turbojet engine. It has both of high efficient noise abatement system and air-cooling system. The air-cooling system prevents burn accidents from high temperature jet

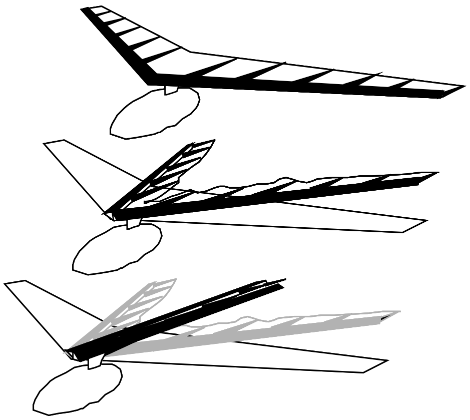

Figure 4. Foldable flexible wing of 3DTR.

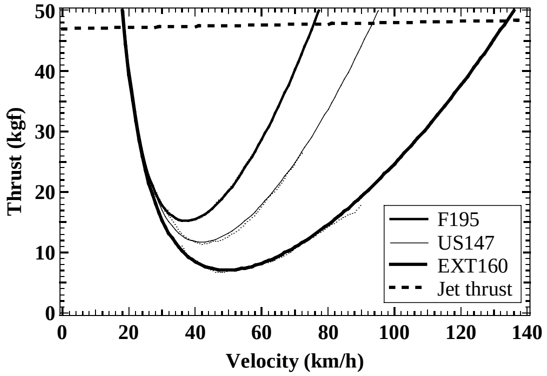

Figure 5. Required thrusts of three flexible wing type and turbojet engine thrust vs. velocity.

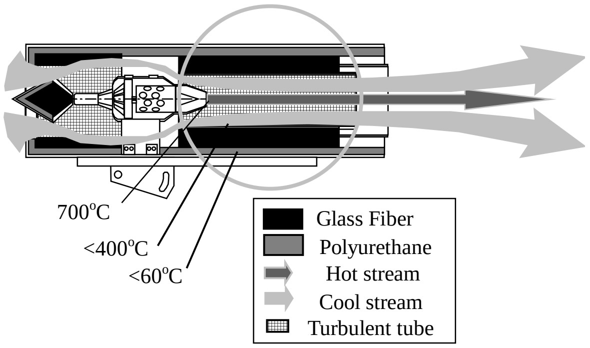

Figure 6. A quiet turbojet engine for 3DTR-II.

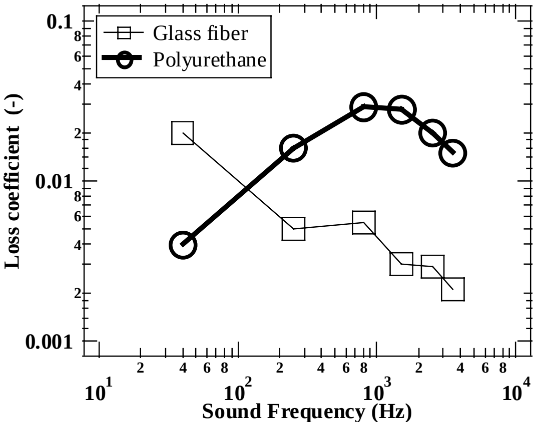

Figure 7.Efficiency of noise reduction materials.

stream. Figure 7 shows noise abatement effects by two kinds of noise reduction materials applied to 3DTR turbojet engine. Glass fiber and polyurethane reduce respectively low and high frequency band noise emission, and a combination of them realizes highly efficient noise reduction.

Figure 8 shows summary of noise reduction effects of the silencer system. Reduced noise level in Fig.8 implies a difference between an original and an improved. Noise levels were measured in front, side and back of turbojet engines at distances of 15m, 30m and 50m. Maximum noise reduction of 20dB was obtained at a side of the improved turbojet engine.

Figure 9 is a field test scene of an experimental prototype called 3DTR-I. Two quiet jet engines were mounted on 3DTR-I. An operator was able to do his work without ear protectors even very close to the running jet engines.

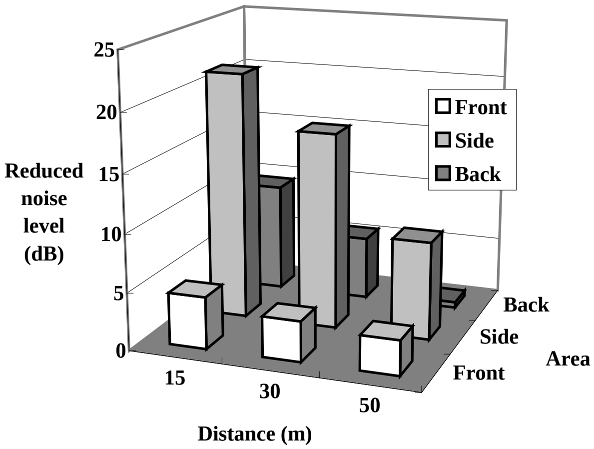

Figure 8. Effects of noise reduction.

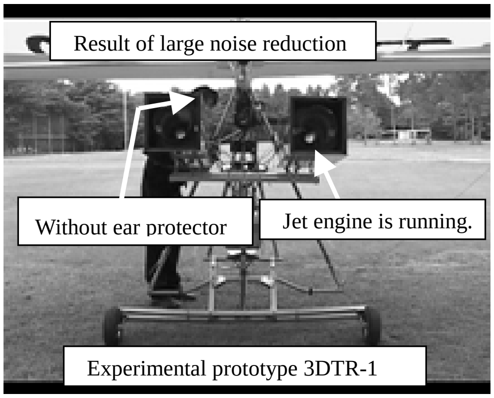

Figure 9. Running quiet jet engines and an operator standing close to them.

Figure 10. Taxing of 3DTR-I on a runway.

III. Construction of 3DTR

Construction of 3DTR-I was started in 2004. The purpose of 3DTR-I construction is to obtain design data on the structure, shape, function, physical stability and strength. The construction work was carried out in a repetitive scrap

Figure 11. The folded 3DTR-I can only occupies a small parking surface area.

Table 2. Specifications of 3DTR-II.

Width	10500mm
Length	3500mm
Height	2500mm
Total weight	95kg
Wheelbase	2000mm
Tread	1800mm
Wheel radius	200mm
Max. engine thrust	230N@108000rpm each
Engine weight	8kg x2 units
Idling rotation	36000rpm
Max. rotation	108000rpm
Engine diameter	320mm
Engine length with silencer	1000mm
Engine response	3.5sec/36000-108000rpm
Actuator: DC motor	48V, 150W x2 units
Battery	12V x 12Ah x4 units

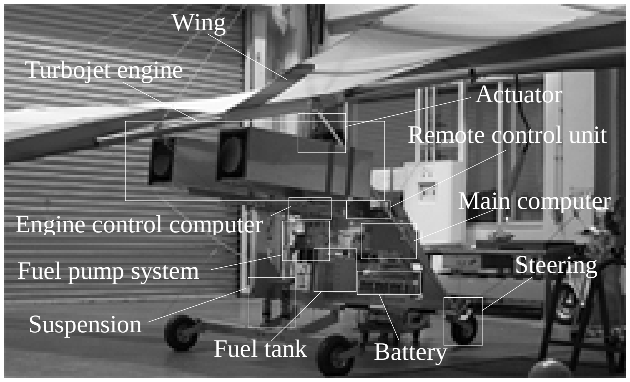

Figure 12. Right rear view of 3DTR-II.

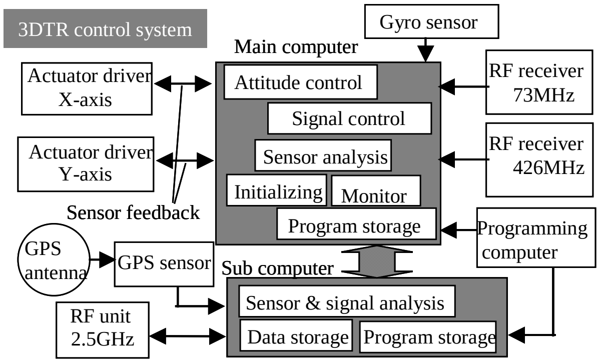

Figure 13. Control system of 3DTR-II

and build manner at an AIST machine shop. In 2005, 3DTR-I was completed and rolled out to a test runway of AIST as shown in Fig.10.

Figure 11 shows the folded 3DTR-I during parking in a garage. 3DTR-I occupied only less than a half area of an automobile parked nearby as shown in Fig.11. This compactness was realized by the flexible wing concept as shown in Fig.4.

3DTR-II was then constructed as a flight test model. It has an improved hull structure in strength with reinforced suspensions and actuators compared with 3DTR-I. Table 2 shows specifications of 3DTR-II. Large wing area of 18.1m^2 is required to carry a certain mount of payload for small cargo transportation.

Figure 12 shows a right-rear view of 3DTR-II. Fuel tanks are located at the center of the hull in order to keep its balance during flight. Four Lead-acid 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 3DTR-II and their large weight of 20kg make the CG of 3DTR-II lower. 3DTR-II is steered by shifting of its gravity center like a pendulum using the roll-actuator. A hull of 3DTR-II acted as a weight of a pendulum and needs some suitable volume in order to keep good stability. A spread foldable wing is jointed to the hull frame through a single point near the center of MAC. The joint between the wing and the hull frame of 3DTR-II consists of roll- and pitch-actuators. Twin quiet turbojet engines are mounted on the upper hull. This thrust point is important to stabilize pitch attitudes of 3DTR-II.

A suspension system consisted of twin coils and dumpers are quite effective for landing shock reduction. Dumping rate can be arbitrary chosen depending on runway conditions. Steering of the front wheel is necessary to keep right direction on a runway for take-off. The main computer mounted on the center of the hull controls vehicle attitude automatically driving the actuated joint. Commands from the operator are transmit to the main computer through the radio signal receiver as shown in Fig.13.

IV. Flight Experiments

Flight experiments were conducted in order to measure take-off speeds and distances and check the corresponding thrusts. On November 22, 2005, 3DTR-II made its successful maiden flight. Figure 14 shows a recent scene to minimize ground-run-distance for take-off. We have accomplished the distance reduction up to 36m in 2006. The take-off speed was 32.4km/h (9.0m/s) and the wing attack angle was 16 degrees. [2,3] 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 3DTR-II. Studies on the take-off characteristics are under way.

Figure 14. Flight test of 3DTR-II.

V. Conclusion

A concept and design data for an UAV for small cargo transportation was proposed, and a flight model of 3DTR was successfully constructed as a prototype UAV for small cargo transportation. Flight experiments have verified the following features of 3DTR-II;

1) 32km/h as the lowest flight speed,
2) 36m as the shortest take-off ground-run distance,
3) Pendulum stability of attitude in the air,
4) Quiet turbojet engines with a newly invented noise abatement system.

The maiden flight was successfully made on November 22, 2005.

Considerably large commercial markets for personal air transportation will be created in the near future and we firmly believe that highly automated small vehicle for personal use will foster a large industry.

Acknowledgments

The authors would like to thank Dr.S.Hirai, Dr.H.Hirukawa and Prof. K.Tanie for useful discussions. This research was partly sponsored the Japan Society for Promotion of Science (JSPS) under Grants-in-Aid for Scientific Research (No.18700203).

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