TAIL-SITTER VTOL UAV
- RESEARCH PROJECT OVERVIEW -

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Abstract

The present study aims at applying tail-sitter VTOL technique to medium-range (MR) class UAVs in order to overcome inconveniences caused by parachute recovery.

This paper describes a general view of the research program and the characteristic features of each prototype model.

1 Introduction

Today a major part of unmanned aerial vehicles (UAVs) of medium size are recovered using parachutes. Poor accuracy of the parachute recovery, together with damages on the airframe at impact, increases workload and turn-around time, which is considered to be one of factors that has been impeding spread of UAVs. To solve this problem, the idea of giving vertical takeoff and landing (VTOL) capability to a UAV and capturing it directly by a recovery apparatus seems somehow promising. The Third Research Center of the Technical Research and Development Institute, Japan Defense Agency, with Fuji Heavy Industries Ltd. , has been working on this subject for years (Fig.1).

2 Chronology of Research Activities

2-1 Basic Conception

Since a net-recovery technique is available for low-speed lightweight UAVs to achieve a precision recovery, the object of the present research is MR class, i.e., jet-propelled UAVs. Various schemes for jet VTOL airplanes are known, as listed in the table 1. The 'tail-sitter', which hovers in a nose-up vertical attitude, is the type in which the first complete vertical-horizontal-vertical VTOL flight in the history, and also the first one by a *jet* aircraft were both performed. This fact could be attributed to its

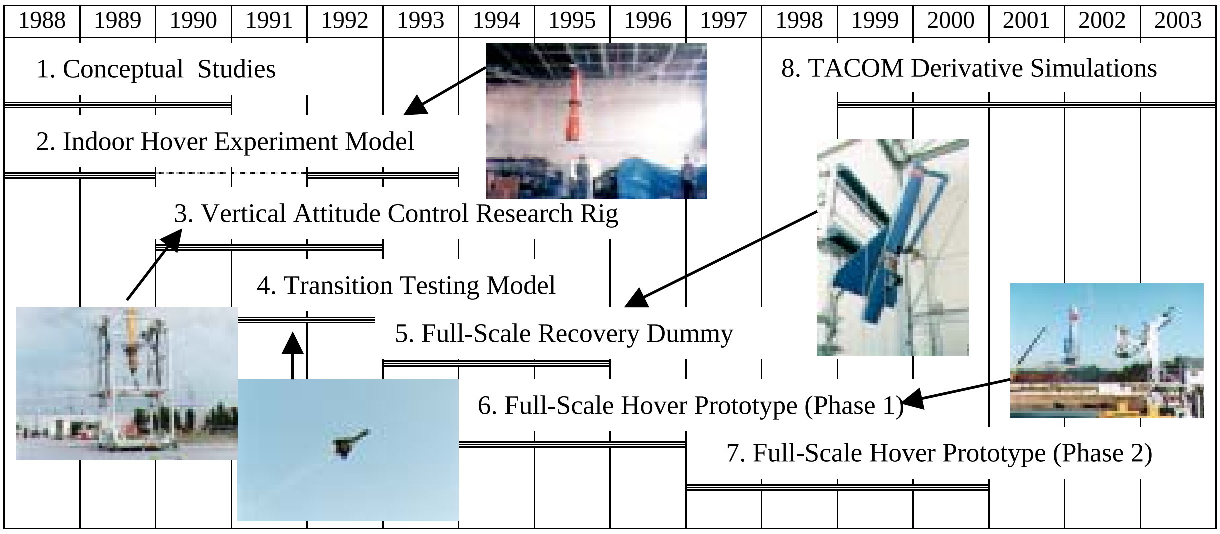
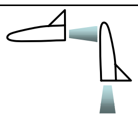
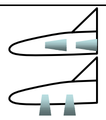
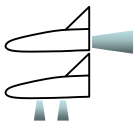
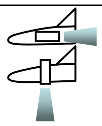


Fig.1 Overall Schedule (Shown in Japanese Fiscal Years)

Table 1 Comparison of Jet-Propelled VTOL Schemes

Type	Advantages	Disadvantages
 Tail-Sitter	・Mechanical simplicity	・Hard piloting ・Rolling takeoff and landing not applicable
 Vectored Thrust		・Specialized E/G required ・Mid fuselage occupied by E/G
 Lift Engine	・Can optimize cruise engine	・Dead weight and space
 Tilting Nacelles		・Single-engine application difficult

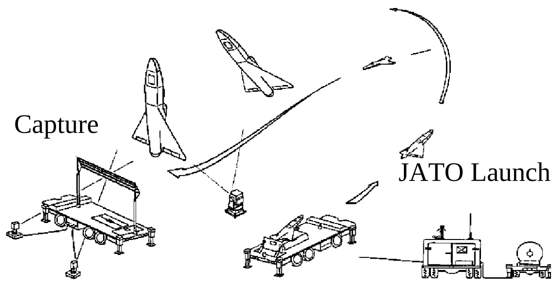


Fig.2 Operational Concept of VTOL-UAV

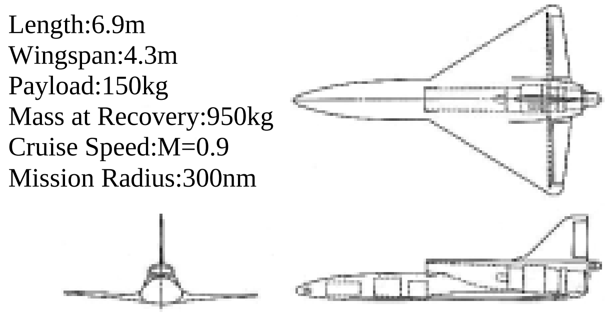


Fig.3 An Example VTOL-UAV Design

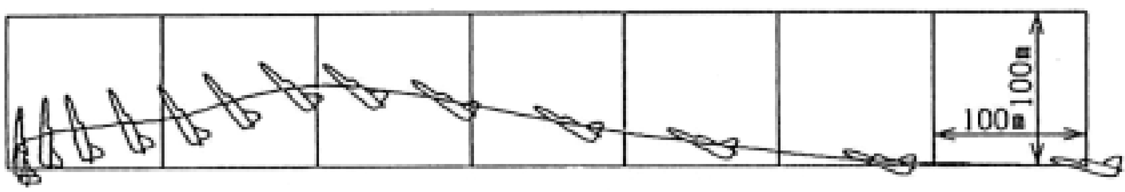


Fig.4 A Simulation of Transition Flight
Note: 2.5sec. intervals. Aircraft is shown in ten times the size.

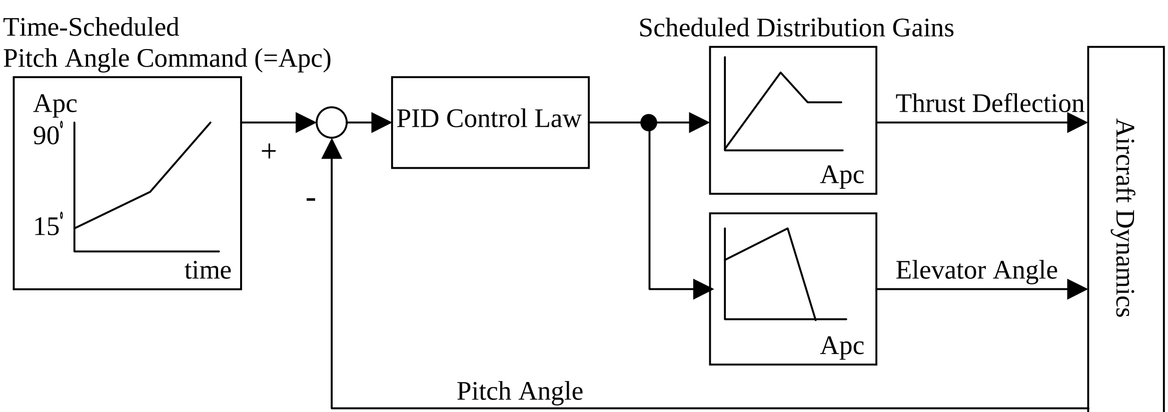


Fig.5 Transition Flight Control Law for Pitch Axis (Not accurate quantitatively)

straightforward clarity of the notion and resulting mechanical simplicity. On the other hand, these performances were realized at the cost of the burden on the side of the pilot. (Backward descent would be impractical for an ordinary pilot…) Also, it will pose much inconveniences in ground handling and servicing. But these problems are of little significance in the case of medium-sized UAVs, if flight control is automated, and its mechanical simplicity and small dead weight are quite attractive for UAVs. Therefore we chose the tail-sitter.

An operational concept of such a UAV is shown in Fig.2. It is conceived that launches are accomplished by means of JATO rocket bottles, since an increase in engine size is quite large if vertical takeoffs are required. Thus we identified following technical elements as essential for the realization of a tail-sitter UAV:

a) Vertical attitude hover flight control
b) Horizontal-to-vertical transition flight control
c) Approach guidance system
d) Capture mechanism

A number of testing prototypes as mentioned hereafter were conceived to investigate these technical elements.

At the first stage of the research we made conceptual studies. As an airframe configuration, a delta-wing with forebody side chines was selected to realize at the same time a high-speed performance and good high angle-of-attack characteristics for ease of transition flight. Although the exact dimension and configuration of the vehicle depend on the operational requirement which isn't yet present, an example UAV was designed for use as a baseline for later stages of the research works(Fig.3). System elements such as guidance system and recovery system including a stabilizing mechanism for shipboard use, were designed.

Control laws for transition flight were studied through simulations using high angle-of-attack wind-tunnel data. Although a zoom-climb followed by a gravity deceleration is the simplest way in terms of control, considering the fuel and time required for a descent to the recovery point, a constant-altitude transition is more desirable. Simulation studies showed that a true constant altitude transition is much hard because at the first portion a very slow pullup is required and at the latter part the engine response is not fast enough to compensate the rapid decrease of the aerodynamic lift. Therefore we devised a pattern in which, allowing a slight climb on the midway, the initial altitude is recovered at the end (Fig.4). An outline of the pitch-axis control law for this transition is given in Fig.5. This is based on a pitch attitude command which increases at constant rates switched at the middle. Control authority is transferred from aerodynamic elevators to thrust vectoring by means of scheduled gains. It should be noted that this scheduling is done with regard to the pitch attitude command which is readily available within the flight control computer, rather than to the actual state.

2-2 Indoor Hover Experiment Model

(1) Attitude Control Experiments

Vertical-attitude hover control was conceived to be executed by thrust deflections. Following preliminary simulation works, a small fuselage-only flying model was fabricated based on radio-control(R/C) techniques to prove the concept. The vehicle has a rear-mounted R/C model engine and a pusher propeller shrouded in a duct. This propulsion system represents a jet engine. There are four vanes at the end of the duct in a cruciform arrangement. These vanes are individually actuated to produce moments in three axes. This is called the 'Cross-Vane System'. A vertical gyro is mounted onboard, of which the data were sent through a tether line to a floor-based personal computer. Flight control computations were executed in this computer and transmitted by a R/C transmitter. During the first series of the experimentation (1988-1989) the feasibility of attitude control by thrust deflections was demonstrated.

(2) Position Control Experiments

In the second series (1992-1993), a position

Fig.6 Position Control Test
Note: Video camera at each end of the beam at the bottom of picture.

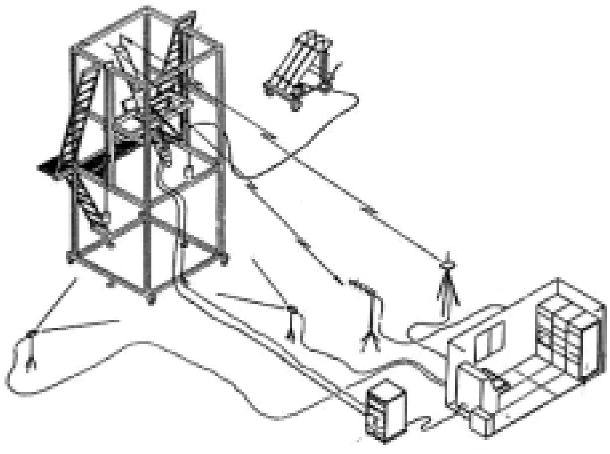
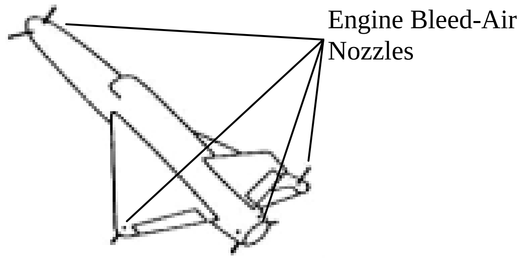
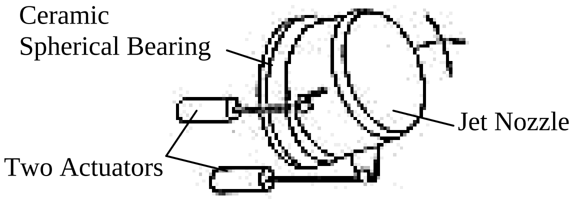


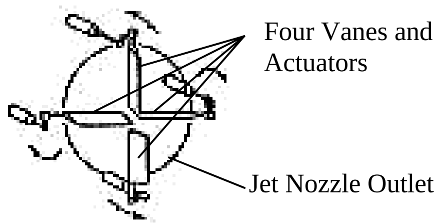
Fig.7 Vertical Attitude Control Research Rig



a) 3-Axis Reaction Control System (RCS)



b) Swivel Nozzle System
(Used with roll axis RCS.)



c) Cross-Vane System

Fig.8 Attitude Control Devices

measurement system was introduced. The system included two laterally separated video cameras fixed at each end of a beam. These cameras were coupled to color extractors which recognize an electric bulb mounted on the surface of the vehicle. Vehicle's position was obtained by triangulation and fed to the flight control to realize a position control. 'Hands-off' hovers were successfully demonstrated. This system formed a basis for the short-range guidance system of later research prototypes.

2-3 Vertical Attitude Control Research Rig

To collect fundamental data regarding vertical-attitude hover controls, a testing rig was fabricated.(Fig.7) The framework made of steel is seven meters high and three meters wide. A four-meter-long simulated UAV, supported in three-axis gimbals, can also slide up and down along vertical rails. The vehicle is equipped with a turbojet engine derived from J/AQM-1 target drone with addition of a bleed-air port and refined thrust control resolution.

Three types of attitude control devices(Fig.8) were prepared for evaluation. Testing consisted of two parts: moment measurements and vehicle control trials. As a result, all of devices functioned as intended. Above all the swivel-nozzle system was found most satisfactory for a thrust deflection angle almost equal to the nozzle angle and virtually nonexistent thrust loss.

A notable point of the cross-vane system is that it has one extra degree-of-freedom. Using it, 'thrust-attenuation' control can be performed by deflecting vanes in scissors-like manner.

In the case of RCS attitude control, a small residual oscillation persisted in each axis. This was an anticipated behavior caused by on-off action of reaction control valves, therefore no problem in itself. But undesirable in the view of waste of bleed-air. Consequently, proportionally-functioning valves were adopted for roll control on the later hover prototype.

Attitude and altitude control laws were also validated.

2-4 Transition Testing Model

Transition from cruise to hover was also demonstrated with an R/C model. The model was basically an winged version of the indoors hover experiment model. Elevons were mechanically linked to horizontal vanes, and rudder to vertical vane. This is not a dynamically-scaled model. It measured 1.9m long and 1.2m wide and weighed around 10kg. It should have weighed 21kg to be dynamically-scaled with the UAV shown in Fig.3. As an autopilot to fit in the model was not available at the time, it was manually piloted. Onboard instrumentation included angle of attack, sideslip angle, accelerations, angle rates, static and total pressures and control positions. For data recording, onboard storage system and telemetry transmitter were available. The latter was heavier but provided more data length. Flight paths were measured externally by a ciné-theodolite system. Various transition profiles, ranging from a simple zoom-up to a constant-altitude one, were demonstrated.(Figs.10 and 11)

Fig. 9 Transition Testing Model

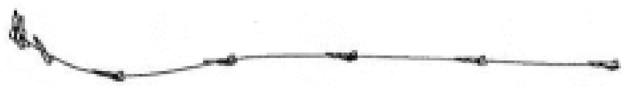


Fig. 10 A Near-Constant-Altitude Transition Performed by the Transition Testing Model
Note: Aircraft are shown in twice the size.

Fig. 11 A Zoom-Up Transition Performed by the Transition Testing Model

2-5 Full-Scale Recovery Dummy

Next, we proceeded to a full-scale flying demonstrator system. (Not full-scale to the Fig.3 UAV but equipped with a full-scale jet engine.) As the first step in this stage, recovery capture mechanism and close-range guidance system were evaluated. Three types of capturing appliances and corresponding UAV-side gears were built (Fig.12):

a) Trap type: Consists of an array of vertical bars in a frame. The UAV has a probe of axisymmetric arrow shape on the belly. When the probe penetrates the frame plane, optical sensors detect it and trigger the trap mechanism. Vertical bars are pneumatically actuated towards the adjacent ones to form pairs ; thus the UAV's probe is grasped by one of these pairs.

b) Harp type: Consists of vertical cords

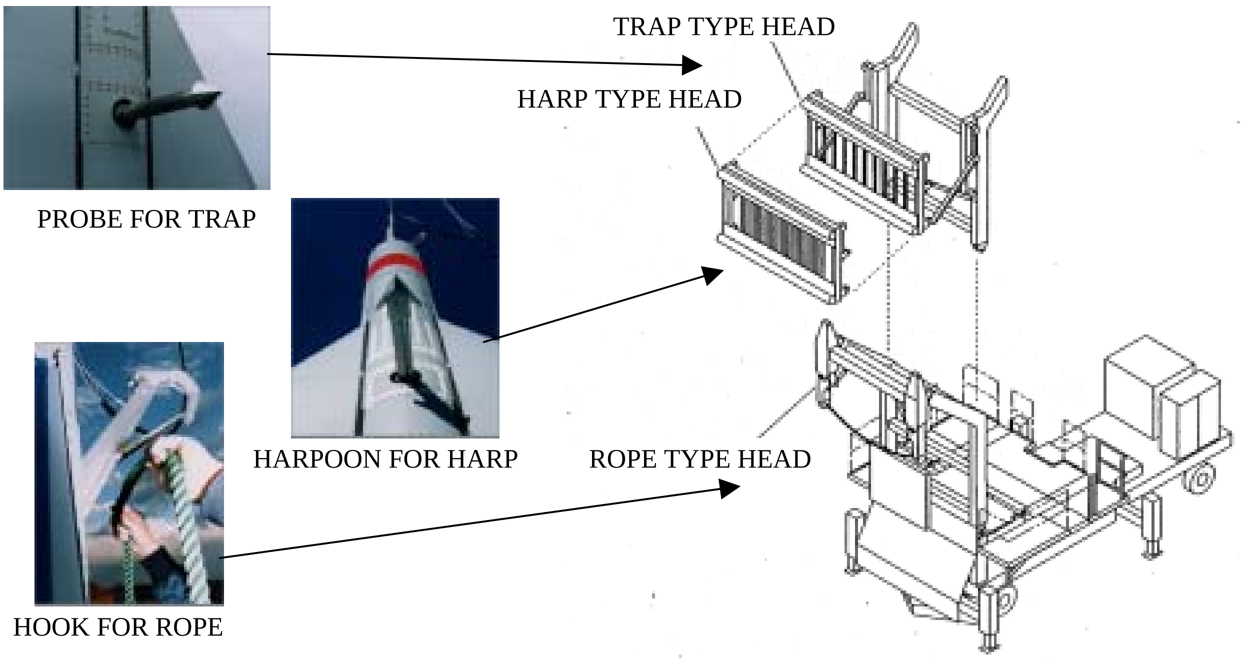


Fig.12 Recovery Apparatus of the Full-Scale Demonstrator System

tensioned in a frame. The UAV has a flat-shaped harpoon with a hook on each side. It penetrates at a speed and captured by cords. No actively actuated mechanisms.

c) Rope type: A rope spans across swinging arms. While the UAV hovers in front of the catcher, the rope swings up to scoop up the UAV's hook.

Short-range optical guidance system (mentioned in the next section) was developed and installed on the recovery apparatus. After evaluation of its own performance, it was used for instrumentation in recovery tests.

A dummy UAV representing the shape and mass properties of the hover prototype was built. The vehicle didn't have an engine nor flight controls. It was equipped with accelerometers at every end of the airframe, an attitude heading reference system(AHRS) and a telemetry transmitter. It was slung and hit against catchers in a large number of combinations of attitudes, velocity vectors and hit points.

Evaluation of recovery systems continued on the phase one of the hover prototype flight tests.

Test results showed that all types successfully functioned with nearly 100% probability of capture. The rope type gave an impression of sluggishness. On some cases with the harp type, the UAV bounced and re-entered in the next interval, causing an interweaving of cords. This resulted in a great effort in releasing the UAV because of the high tension of the cords. In contrast the trap type was most favored in terms of rapidity and reliability.

2-6 Full-Scale Hover Prototype

Flight testing of the full-scale hover prototype consisted of two phases.

The objective of the phase one (1994-1996) was evaluation of vertical-attitude hover control, short-range guidance system and recovery mechanisms.

Since this system is intended only for hover

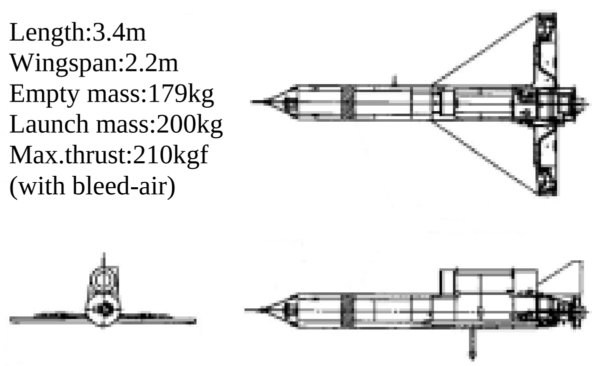


Fig.13 Full-Scale Hover Protorype

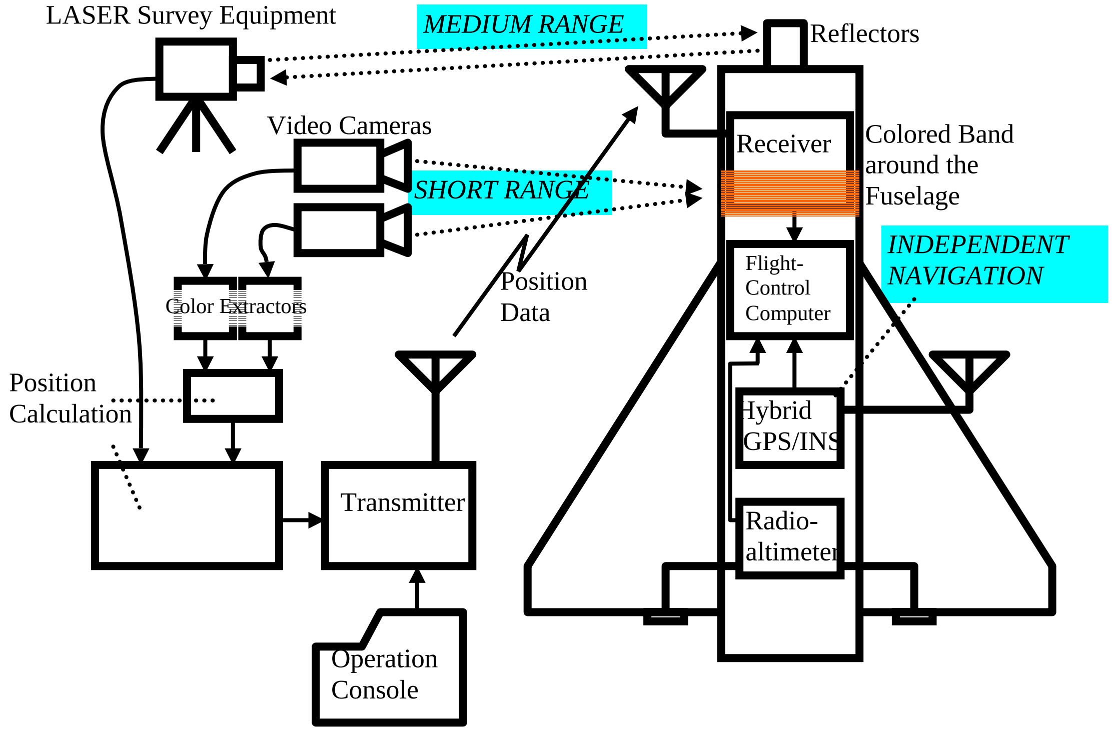


Fig.14 Guidance System of the Full-Scale Hover Prototype Phase Two

flight, the air vehicle(Fig.13) has a cylindrical fuselage and a flat-plate wing section. It is equipped with swivel-nozzle thrust vectoring plus roll-axis reaction control system.

In the phase two(1997-2000), a medium-range guidance system based on a off-the-shelf LASER survey equipment and DGPS-INS hybrid navigation system were added and transfer between guidance modes were demonstrated.(Fig.15) In this phase, only the trap type recovery mechanism was used.

The full-scale hover prototype system will be discussed in details in another paper.

Fig.15 Full-Scale Hover Prototype Flight Test

3 Conclusions

Essential technologies of the tail-sitter VTOL-UAV have been developed and demonstrated through various research works. We consider this technique can expand application areas of medium-sized, high-speed UAVs.

We are pursuing an idea to use the TACOM multi-purpose platform(Fig.16) as a design basis to build a full - flight - capable VTOL

Fig.16 TACOM Multi-Purpose MR Platform

demonstrator. Its conceptual design studies and flight simulations are being conducted.