Micro Craft Ducted Air Vehicle

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Abstract
Recent military and commercial interest in Unmanned Air Vehicles has inspired the design of a unique Vertical Take-off and Landing (VTOL) Micro Air Vehicle (MAV). This vehicle, the Micro Craft Inc. iSTAR consists of an annular wing (duct), upper and lower center-bodies, a fan, and vanes at the end of the duct to provide control. Micro Craft Inc. is developing a 9-inch diameter iSTAR (iSTAR-9) under the DARPA Micro Air Vehicle program and will soon begin the flight test program. This vehicle not only takes-off and lands vertically, but flies at speeds up to 60 kts by pitching over to a near horizontal attitude. Total vehicle weight is 3.1 lbs including two video cameras and full fuel.

Introduction
The Micro Craft Inc.1 iSTAR Vertical Take-Off and Landing air vehicle (Figures 1-3) combines the utility of a helicopter with the high speed cruise capability of a fixed wing aircraft. Its VTOL capability eliminates the need for large, improved landing fields or complex launch and recovery systems. The ability to fly very slowly enables static or slowly moving targets to be easily tracked. By pitching over and flying at high speed, distant targets can be reached quickly. In addition the iSTAR can land and shut down the engine to monitor fixed targets for extended periods of time. This versatility is achieved without the complex propulsion and mechanical systems inherent in other VTOL designs. There are no gearboxes, articulating blades, counter-rotating propellers, or tail rotors. The high thrust-to-weight ratios required for hover and low speed flight are achieved using a single ducted fan for propulsion. Lift in forward flight is generated by the annular wing (i.e., duct) which is more efficient than a conventional planar wing of the same span. Military applications for this vehicle include intelligence, surveillance, targeting, acquisition and reconnaissance as depicted in Figure 4. Commercial applications include border patrol, bridge inspection and police surveillance.

Many aircraft have utilized ducted fan technology to hover successfully. However most of these aircraft did not attempt to transition to high speed forward flight. Probably the most successful was the Bell X-22, first flown in 1965 (Figure 5). The X-22 consisted of a fuselage and four ducted fans that rotated relative to the fuselage to transition the vehicle forward. The X-22 flew for over fifteen years logging 220 flights including 386 vertical take-offs and 185 complete transition cycles. The X-22 differed from the iSTAR in that it had planar tandem wings and a fuselage that remained level in flight.

One of the first aircraft using an annular wing for direct lift was the French Coleoptere built in the late 1950s. This vehicle (Figure 6) successfully completed transition from hovering flight using an annular wing, however a ducted propeller was not used. Instead a single jet engine was mounted inside the centerbody for propulsion. Control was achieved by deflecting vanes inside the jet exhaust.

Less well-known are the General Dynamics ducted-fan Unmanned Air Vehicles developed and flown starting in 1960 with the PEEK aircraft (Figure 7). These vehicles demonstrated stable hover and low speed flight in free-flight tests, and transition to forward flight in tethered test configurations.

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1. Micro Craft Inc. is a division of Allied Aerospace Industry Incorporated (AAII)
ground tests. In 1999 Micro Craft acquired the patent, improved and miniaturized the design, and manufactured two 9-inch diameter flight test vehicles under DARPA funding. Micro Craft will soon be entering the flight testing phase of the program with these vehicles. In addition to the flight test program Micro Craft and NASA-Ames are cooperatively undertaking a research and development program to improve the design by optimizing the duct and fan geometry and developing a flight simulator for control system optimization.

**The iSTAR-9 Flight Demonstration Aircraft**

The iSTAR-9 (Figures 1-3) is a unique demonstration/proof-of-concept VTOL aircraft designed and built under the DARPA MAV program. A ducted fan is used for lift and for propulsion. The duct increases the propeller efficiency in all modes of flight. Additionally as the vehicle is pitched over to attain high forward speed (Figure 8), the duct generates lift similar to a conventional wing. This configuration has two additional benefits: it has a small footprint and is inherently safe to operate due to the duct protecting ground personnel from the rotating propeller. Because of the absence of complex mechanisms common with other VTOL aircraft (counter-rotating propellers, gearboxes, articulating blades, etc…) the iSTAR also benefits from a reduced part count contributing to improved reliability, low structural weight and low cost.
Vehicle Description

The iSTAR-9 is composed of four major assemblies as shown in Figure 9: (1) the duct containing fuel in the leading edge, four control vane servos, and avionics (2) a lower center body housing additional avionics, (3) the upper center-body containing the engine, batteries and payload, and (4) the landing gear. Both center-bodies are attached to the duct (not to each other) using vibration and thermal isolators. This provides excellent isolation between the engine and avionics. Eight fixed stators span the duct to reduce the engine torque (i.e., reduce swirl velocities). Control vanes attach to the trailing edge of the stators, providing roll, yaw and pitch control. The majority of the structure has been fabricated from Kevlar and graphite based composite material, which results in a very strong, lightweight airframe. For example the duct weighs only 117 grams, but is an extremely rigid structure. The Gross Take-Off Weight of the iSTAR-9 is approximately 1400 grams (3.1 lbs), including payload and 200 grams of fuel.

The propulsion system is a commercial-off-the-shelf (COTS) OS-32 SX single cylinder, two cycle engine turning a two blade carbon composite propeller. This engine develops 1.2 hp and weighs 250 grams (~0.5 lb.). A propeller gearbox is not used. Maximum thrust is approximately 4.3 lbs using a fuel mixture of nitro-methane, alcohol, and oil. Starting the engine is accomplished by inserting a cylindrical shaft with an attached gear into the upper center-body and meshing it with a gear fit onto the propeller shaft. The shaft is rotated using an off-board electric or air motor (an operational vehicle would include an on-board starter which would enable the iSTAR to land and shut down the engine, monitor a target for an extended period of time, then restart the engine and continue the mission).

Avionics/Electronics

Airborne avionics consists of the Flight Control Computer (FCC), sensors, up-link and down-link receiver and transmitter, two video cameras and one video transmitter. Sensors include three micro gyros, three micro accelerometers and one three axis magnetometer. The pilot does not have direct control of the control surfaces. His commands along with the sensor data are input into the FCC. The computer then deflects the surfaces to follow his steering commands and stabilize the vehicle. With this approach the pilot workload is minimized, eliminating the need for extensive pilot training.

The payload consists of two COTS micro video cameras located in the nose and duct and one video transmitter (see Figure 10). These color cameras operate on 5 volts consuming 160 mA, weigh 8 grams, and transmit on a frequency of 900 MHz. Each has a field of view of approximately 70 degrees with a resolution of 350 lines.

Four servos are located in the duct to actuate the control surfaces. These servos are quick in response (slew rate), but are low in bandwidth relative to typical UAV and missile servos. Bandwidth is defined by how well the servo output follows a sinusoidal input signal. For all servos the output lags behind the input and the signal degrades in magnitude as the frequency increases. Figure 11 shows the frequency response for the baseline iSTAR-9 control surface servos. At low frequency the output signal lags by approximately 30°, increasing to 90° at 8 Hz. Although the bandwidth is less than desired and the size of this servo larger than originally intended, it is the best among the sample of low-cost, COTS miniature servos tested. Smaller servos could not be used due to their large mechanical free-play, large electrical dead-band, and even worse frequency response.
The performance requirement for the throttle servo is not as stringent. This is primarily because the pilot controls the throttle servo directly. Since humans are relatively slow in response time (typically 4 Hz) it is not necessary to use a high performance servo. As a result a much smaller servo could be used; The throttle servo is approximately 60% of the size and less than one-fourth of the weight of the control surface servo.

Aerodynamics
During horizontal flight the duct generates lift similar to a conventional planar wing. In fact an annular wing (i.e., duct) generates half the induced drag of a planar wing of identical span (Oswald efficiency factor = 2.0). Annular wings also stall at much higher angles-of-attack as shown in Figure 12: approximately 14° for a planar wing versus 35° for the iSTAR-9. The annular wing also has very benign stall characteristics, which enables the iSTAR to fly at any given speed throughout the flight envelope.

The upper curve in Figure 12 represents the lifting force with power on. Adding power increases lift dramatically for two reasons. First, it reduces or even eliminates separation by energizing the boundary layer. This is a significant effect and is most prominent at moderate angles of attack where separation occurs. Secondly, a component of the thrust acts in the lift direction. At low angles-of-attack this thrust effect is small and the aerodynamic lift primarily supports the vehicle. At high angles the thrust alone supports the vehicle.

Propulsion
The duct not only develops lift externally but also improves propulsion efficiency. Compared to an open propeller of identical span, a ducted propeller generates higher mass flow rates leading to higher thrust levels and efficiencies. Figure 13 shows the total thrust and the proportion contributed by both the duct and propeller. At 18,000 RPM the propeller generates 80% of the total thrust. The remainder is generated by the suction on the leading edge of the duct itself. These data were generated at static conditions using a full scale wind tunnel model powered by an electric motor. The propeller used for this test was not optimized for duct flow. A COTS open propeller was modified slightly by squaring the tips as shown in Figure 14.
Flight Testing
Flight testing is scheduled to begin in September 2000 in San Diego. Testing will begin with hovering flight, progressing to a perturbed hover, and finally to high speed forward flight. Initially a tether will be used to minimize risk to the vehicle and avionics. This will be a very light-weight safety tether only, not an electrical tether, and will not influence the flight of the vehicle. Following successful completion of these tests the tether will be removed and the iSTAR will be flown in free flight.

The iSTAR demonstrator will initially be flown in a ‘pilot assist’ mode. In this mode the ground pilot issues commands through a conventional controller (two joysticks, slider bars, etc..) which are then sent through a serial cable to the ground control station. The ground control station converts the commands to a Pulse Width Modulation (PWM) signal and transmits them through RF link to the vehicle.

Fully autonomous flight will be completed in later phases of testing. In these tests a ground operator will pre-plan the mission using waypoint steering. Both take-off and landing will be accomplished autonomously, without pilot input. GPS will be added for navigation, along with a upgraded sensor suite and digital up-link and down-link capabilities.

Future Development
In addition to exploring and expanding the envelope through flight testing, Micro Craft Inc. is embarking on a research and development program to increase the mission effectiveness of the operational vehicle. Low acoustic levels may be critical for some missions. To this end, the acoustic signature is being mapped (varying engine speed, attitudes and distances from the vehicle) and methods to reduce the acoustic signature are being studied. In a cooperative program with NASA Ames, Computational Fluid Dynamic (CFD) techniques are being used to reduce the acoustic signature and optimize thrust through modifications of the duct and propeller.

Studies are also underway to determine the benefit of adding gear reduction to turn the propeller at lower speeds. These studies, using Micro Craft’s proprietary ducted propeller performance code (MDPROP), show that a higher solidity fan turning at a lower speed will reduce noise levels significantly with very little thrust loss.

In addition to the CFD studies mentioned above, NASA-Ames is also developing a flight simulator using their in-house code RIPTIDE and assisting in control system optimization using linear and non-linear control modeling.

One area that needs further attention is servo-actuator development. Many of the MAV program participants are using COTS ‘hobby’ type actuators. These actuators are easily obtainable and inexpensive but are not built to military specifications and were not designed to withstand a battlefield environment. Furthermore their performance is lacking with respect to typical industrial grade commercial or military servos (in terms of reliability and bandwidth). A program to develop higher quality miniature actuators would be beneficial for all Micro Air Vehicles.

The iSTAR Operational Aircraft
Vehicle description
The operational iSTAR aircraft will be similar to the current flight test/demonstration aircraft with a few exceptions to improve performance, handling and producability. Because of the lack of availability of nitro-methane fuel in the field, the current engine will be replaced by a diesel engine burning JP-8 fuel. These engines are currently being developed by DSTAR Engineering under DARPA funding. An onboard starter would also enable the aircraft to land, shut down the engine to observe a target for an extended period of time (“Perch & Stare”), and then restart to continue the mission.

Fan optimizing studies are currently in progress which may result in the use of high solidity fans for low acoustic signature and improved thrust. As a result, the operational vehicle could use a three or four blade propeller with a larger chord, and possibly a gearbox to reduce the propeller speed.

For producability and lower cost, much of the structure will be manufactured from thermoplastics instead of composite. Payloads would vary depending on the mission, however multiple micro-
video cameras and small un-cooled infrared cameras will be common sensors. Current infrared cameras weigh less than 0.5 lb, and research is ongoing to reduce their weight and size further. Other payloads include repeaters and chemical ‘sniffers’. Tracking and monitoring devices or even small pyrotechnic devices (mines, bombs, etc..) could also be deployed from the lower center-body or duct.

Concept of Operation
In a typical mission the operator will remove the vehicle from the storage case (fully fueled), place it on the ground, and then plan the mission using the ground control station. Navigation waypoints would be entered on the ground control station using a touch screen. When commanded to begin the mission the engine would start and the mission flown fully autonomously, using a GPS aided Inertial Navigation System (INS). No flight training will be required for the operator. The vehicle could be commanded to return home or to eliminate the return leg to extend the range, where it would be either sacrificed or retrieved at a later time. Real-time sensor information would be transmitted back to the operator or other personnel directly or through ground or airborne relays.

Performance
The operational iSTAR has an endurance of approximately 1 hr, a range of 60 nm (one way) and a maximum speed of 60 kts. The operational vehicle will have a number of improvements that make this performance possible. First, additional fuel will be available. The minimum thrust-to-weight ratio required for hovering and forward flight is 1.2. The flight test demonstration aircraft has a thrust-to-weight ratio of 1.39 with full fuel. Although such a high thrust-to-weight ratio was desirable for flight testing purposes, it is not necessary for an operational aircraft. The excess thrust margin will be converted into payload and/or fuel to increase mission range and endurance. For a nine inch diameter vehicle this correlates to an additional 210 grams of fuel (from 200g to 410g). Another advantage of the operational vehicle is the engine. A diesel (JP-8) burning engine would be used, which are significantly more efficient than nitro-methane burning engines.

It is important to note that these performance figures are for a nine-inch diameter iSTAR. Depending on customer requirements, the operational vehicle could be slightly larger or smaller than the demonstration vehicle.

Concluding Remarks
A new and unique VTOL aircraft, the Micro Craft Inc. iSTAR, is in development that has tremendous potential for military and commercial applications. Benefits of this vehicle include the following:

- Vertical landing and take-off
- High speed cruise
- Small footprint
- Low complexity (low part count, low cost, increased reliability)
- Scaleable design
- Inherently safe to operate (shrouded propeller)

Payloads include video and infrared cameras, repeaters, and chemical ‘sniffers’. Tracking and monitoring devices or even small weapons (mines, bombs, etc..) could also be deployed from the lower center-body or duct. An operational vehicle would be flown autonomously, eliminating the need for pilot training. Sensor information would be sent to the operator to be viewed real-time or stored for later analysis.
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History
Program Overview
Vehicle Description
Flight Video
History

- **PEEK**
  - 1961

- **Hover/Low Speed Translation**
  - First Demonstrated in 1965

- **RTV**
  - 1976

- **RWV**
  - 1993

- **MCI acquires Patent, Develops MAV, 1999**
Program Overview

- DARPA Funded
- MCI-Sanders-NASA/Army
- 2 Vehicles built
- First Flight: 10-6-00
- Flight Testing In Progress

First Flight
• **Analyzed and tuned control laws (CONDUIT)**
  - Attitude command
  - Rate command
  - Rate command with heading hold
  - Gain optimization with specified constraints

• **Modeled Hardware Characteristics**
  - Actuator dynamics
  - Sensor models with noise and drift

• **Flight Simulation (RIPTIDE)**
  - Control system trade studies
  - Pilot-in-the-loop Simulation/training
Benefits

- Vertical take-off & landing
- High speed horizontal flight
- Inherently safe to operate
  - duct protects personnel from propeller
  - duct protects propeller from FOD
    (can operate in vicinity of obstacles)
- Small footprint / Easily containerized
- Simple design (low part count = reliable + low cost)
- Duct increases propeller efficiency & provides lift
  (similar to planar wing)
Manufacturing (MCI- Ontario)

- Engine, Prop, Duct LE and Upper Center-body
- Center-bodies and Mold
- Composite Duct
Vehicle Description

- 9” outside duct diameter
- 3.3 lbs GTOW
  - Empty Wt = 2.9 lb.
  - Fuel: 0.4 lb.
- 1.2 hp 2-cycle engine
- Max speed 60 kts
Propulsion

Baseline Engine
OS-32 SX
1.2 hp @ 18,000 rpm
270 grams
Engine Starting

Flight Test Vehicle
External motor/shaft

Operational Vehicle
On-Board Starter
Fuel System

- Wet Leading Edge (similar to conventional wing)
- Sump
- Non-Structural
COLOR MICRO-VIDEO CAMERA/TRANSMITTER

- 350 lines of resolution
- 20 grams
- 1.02” x 0.86” x 0.7”
Avionics Integration

- 3 piezo-electric gyros
- 3 accelerometers
- 1 magnetometer (3-axis)
Avionics Integration: Processor Board

- Infineon Processor (16 bit, 20 MHz)
- 10-bit A/D converters
- PWM generator
Flight Testing

First Flight

Tether System
VIDEO
FIRST FLIGHT
Future Plans

- Complete low and high speed flight testing
- Acoustic signature reduction
  - muffler design
  - reduction of prop speed
  - low speed fan design
  - Absorbing materials in the duct
- Remote restart capabilities
- Heavy fuel conversion (JP-8)
- Fully autonomous flight