The use of active flow control devices that affect the flow field over the wing and tail planes sufficiently to create moments and forces that can be used for controlling the aircraft has attracted interest over the last decade. Using flow control actuators to control aircraft attitude have several potential benefits as compared to conventional control surfaces. These benefits are in reduced structural weight, lower power consumption, higher reliability and potentially faster response times. This paper presents preliminary flight test results and lessons learned concerning the use of flow control actuators for both open and closed loop control of the DragonEye UAV.

I. Introduction

The use of flow control actuators for flight control has been studied extensively over the past decade. Research on open-loop flow control has demonstrated the control effectiveness of flow control actuators on both static and rigidly moving test platforms. A majority of the research that has been done have focused on the mitigation of flow separation over wing sections or on flaps [1, 2]. An experiment has been performed to control the wing rock dynamics of a delta wing at post-stall using tangential Leading Edge Blowing. The lift and drag benefits associated with flow attachment to enable control in a broader angle-of-attack range has been demonstrated. However these methods still rely on conventional control surfaces for attitude control of the aircraft or wing section. A different approach to flow control that emphasizes fluidic modification of the apparent aerodynamic shape of the surface by exploiting the interaction between arrays of surface-mounted synthetic jet actuators and the local cross flow was recently developed [3, 4]. With this approach bi-directional pitching moments can be induced by individually controlled miniature, hybrid surface actuators integrated with rectangular, high aspect ratio synthetic jets that are mounted on the pressure and suction surfaces near the trailing edge [5]. An important attribute of this technique is that it can be effective not only when the baseline flow is separated but also when it is fully attached, namely at low angles of attack such as at cruise conditions. In our recent studies we have demonstrated successful closed-loop control of pitch motion of a 1-DOF and 2-DOF wind tunnel model using only flow control actuators [6–8]. Additionally, a simple model for the flow control actuators derived from a reduced order vortex model has been used for achieving flight control at a higher bandwidth both with and without adaptive control [9, 10]. Most of the previous work that has been accomplished in the past has been conducted in the wind tunnel that approximates but does not replicate free flight to sufficient accuracy to allow investigation of high bandwidth flight control. In this paper we present flight test results of both closed and open loop flight control on the Dragon Eye UAV.

II. Dragon Eye UAV

In order to test the effectiveness of flow control actuators for closed loop flight control of a highly maneuverable UAV, the DragonEye (see Figure 1), was chosen as the UAV on which to mount the flow...
control actuators. The Dragon Eye UAV is a small tailless fixed wing aircraft with elevons mounted on the wings for both pitch and roll control. The Dragon Eye has a large vertical fin for adequate yaw damping due to the unavailability of a rudder. The UAV is powered by twin engines mounted on the wing. The production UAV has a wing span of approximately four feet and weighs around 6 pounds. It was modified to evaluate the use of flow control actuators for flight control. In order to accommodate the flow control actuators, the wing span was extended by 18 inches with the flow control actuators placed outboard of the elevons. This design enabled using either the elevons or flow control actuators (or both) to control the aircraft in pitch and roll axes. The extension of the wingspan necessitated an enlarged vertical stabilizer to provide adequate damping in yaw. The design uses two electric motors for propulsion. The same large battery pack that provides power to these motors is also utilized for the flow control actuation by the addition of custom power conditioning electronics. In order to evaluate the use of flow control actuators for flight control the Dragon Eye was instrumented with the Adaptive Flight Inc (AFI) FCS20 autopilot system shown in Figure 2 originally developed by the Georgia Tech UAV Research Facility [15]. The FCS20 embedded autopilot system comes with an integrated navigation solution that fuses information using an extended Kalman filter from inertial measurement sensors, Global Positioning System, and air data sensor (total pressure and static pressure) to provide accurate state information. The available state information includes velocity and position in global and body reference frames, acceleration, roll/pitch/yaw rates, barometric altitude, air speed information, and wind estimate. These estimates and measurements can be further used to determine aircraft velocity with respect to the air mass and flight path angle. The Dragon Eye can communicate with a Ground Control Station (GCS) using a 900MHz wireless data link. The GCS serves to display onboard information as well as send commands to the FCS20.

An elaborate simulation environment has also been designed for the Dragon Eye. This environment is based on the Georgia Tech UAS Simulation Tool (GUST) environment [16]. A guidance system is provided onboard the FCS20 to generate a path/trajectory for the aircraft to track. The guidance system calculates the desired airspeed, altitude and a prescribed course which are specified by waypoint locations with associated leg speeds and altitudes. Waypoints are normally uploaded from the ground control station. This guidance algorithm provides the control system with acceleration commands in the air-relative velocity frame. The control system then converts these desired acceleration commands to elevon and throttle commands. The guidance and flight control algorithm that was used in the Dragon Eye has been adapted from the GT TwinStar aircraft [17] which is a conventional twin engine aircraft. The flight control algorithm was modified to use elevons for control around the pitch and roll axes as opposed to using elevators and ailerons on the GT Twinstar. Additional modifications in the flight control algorithm enabled flight using either conventional surfaces for flight control or the flow control actuators for the Dragon Eye UAV, or both in any combination per axis. The flight controller for the GT TwinStar or Dragon Eye-based test aircraft is augmented with different adaptive control schemes that have been developed at Georgia Institute of Technology. These adaptive control schemes have been flight tested and improve on the performance of the baseline flight controller [11–14]. Due to the fact that the guidance and control algorithms and hardware for the Dragon Eye system have been adapted from the GT TwinStar, it is possible to test these adaptive control algorithms with flow control actuators being used for flight control with relative ease, with the implementation previously verified.

III. Flight Test Results

The first tests with the Dragon Eye test aircraft were flown with an instrumentation arrangement that allowed only for recording onboard data. All these flights were flown by a safety pilot utilizing either the elevons or flow control actuators for the pitch and roll axes. These flights verified that the flow actuation system provided some, though limited, effectiveness in this installation. These flights also verified the airframe itself as a viable platform for the desired tests. The next step was to add the instrumentation described in the previous section to enable closed loop flight testing. An additional ten further flights took place with the fully instrumented and updated Dragon Eye-based test aircraft. The first of these flights led to the conclusion that it was necessary to perform flow control actuation tests early in flights, due to the drop in available battery voltage. The first flights also verified all other functionality, including closed loop guidance and control utilizing the elevons and the data recording system. The second tests series included having the external human pilot manually put in large flow control actuation inputs to measure the response. The data shown in Figure 3 is typical, which shows how roll flow control actuation effects roll rate (angular velocity).
This data was subsequently utilized to improve the simulation model in GUST utilized to prepare for flight test activities. In addition, the flow control actuation power conditioning was subsequently enhanced to improve the effectiveness of the flow control actuators. The final flights under this effort included a repeat of the manual control effectiveness tests, shown in Figure 4. The effectiveness in the roll channel does not appear to be dramatically different than in Figure 3. However, there is clearly a response in both axes to these inputs. Note that the aircraft is effectively also being maneuvered to stay on a desired ground track over the field using only the flow control actuation as it flies a considerable path length under only flow control actuation, with both throttles at approximately 50 percent. Only a single data recording file is available for the DragonEye-based test aircraft in the described configuration with the autopilot engaged, shown below in Figure 5. This flight was flown at 80 ft/sec, switching from elevons to flow control actuation (both axes) at approximately 16 seconds. Both inputs saturate fairly quickly. The aircraft maintained altitude, but did not remain on the desired lateral path. The system was returned to elevon control at the end of the plotted time frame. The lack of effectiveness compared to Figure 5 could be due to the difference in airspeed, but is more likely due to battery discharge reducing the voltage available for flow control.

**IV. Future Work and Conclusions**

In the course of developing the DragonEye-based test aircraft for testing flow control actuators, a number of compromises were made, and lessons learned. As for compromises, the flow control actuators need a large amount of power for their operation in flight. This necessitated the use of a heavy battery which in turn led to an increase in weight as well as the inertia of the aircraft. One other drawback was the limited battery life which lead to relatively short test flights with the flow control actuators. One other drawback observed with the flow control actuators was as the battery discharges, the control authority available with flow control actuator deteriorates with time. In addition, the large wing span of the Dragon Eye combined with short span used for flow control actuation limited the control authority of the flow control actuators. The following lessons were learned from using flow control actuators for flight control they are:

- Current state of the art flow control actuators require large amount of power to operate.
- The use of an existing airframe, The Dragon Eye, compromised the performance of flow control actu-
The use of a heavy airframe and the need to carry a heavy battery to power the flow control actuators limited test flight cycles. Some of the limitations observed during flight test of flow control actuators on the Dragon Eye can be overcome by designing an airframe that can provide improved control authority using flow control actuators. Future research in the use of flow control actuators for flight control include theoretical models that can be used to predict control authority with flow control actuation and using these models in designing new airframes. An additional area of research is in the development of more efficient flow control actuators such that they can be mounted on small fixed wing UAVs.

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References

Figure 3. Control Authority of Flow Control Actuator in the Roll Channel

The roll rate response observed in flight with full flow control actuation is presented in the figure above. Using flow control actuator does induce a non-zero roll rate, however the maximum roll rate observed is much lower than that obtained using conventional control surfaces.

Figure 4. Control Authority of Flow Control Actuator in the Roll and Pitch Channel at 100 ft/s with Manual Control

The figure above depicts the pitch rate and roll rate obtained using only flow control actuators in radio control mode. Note that the elevons are at a constant deflection, control is provided purely through flow control actuators.

Figure 5. Control Authority of Flow Control Actuator in the Roll and Pitch Channel at 80 ft/s with Autopilot

The figure above depicts the pitch rate and roll rate obtained using only flow control actuators in autonomous mode. The deflection observed in the elevons is due to the fact that the elevons were used to trim the aircraft in flight before control was transitioned to full flow control actuation.