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# Greased Lightning (GL-10) Flight Testing Campaign

*William J. Fredericks, Robert G. McSwain, Brian F. Beaton, and David W. Klassman*
*Langley Research Center, Hampton, Virginia*

*Colin R. Theodore*
*Ames Research Center, Moffett Field, California*

July 2017

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National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

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# 1 Abstract

Greased Lightning (GL-10) is an aircraft configuration that combines the characteristics of a cruise efficient airplane with the ability to perform vertical takeoff and landing (VTOL). This aircraft has been designed, fabricated and flight tested at the small unmanned aerial system (UAS) scale. This technical memorandum will document the procedures and findings of the flight test experiments. The GL-10 design utilized two key technologies to enable this unique aircraft design; namely, distributed electric propulsion (DEP) and inexpensive closed loop controllers. These technologies enabled the flight of this inherently unstable aircraft. Overall it has been determined thru flight test that a design that leverages these new technologies can yield a useful VTOL cruise efficient aircraft.

# 2 Motivation for Research

For many decades the aviation industry has been attempting to build a vehicle that can combine the speed and efficiency of an airplane with the VTOL capability of a rotorcraft.

Rotorcraft are able to deliver goods and people to locations that are not accessible to other types of aircraft. Specifically, they are able to land in confined unprepared areas with grass or soft soil because of their relatively low induced velocities through the propulsor, unlike jet propelled fixed VTOL aircraft. In addition, they have a minimal disturbance from gusts because, unlike a ducted propulsor, that gust can travel edgewise through the rotor disk imparting minimal forces and moments on the aircraft. Moreover, rotorcraft have the best hovering performance because of their low disk loading. As one can see in Figure 1, at lower disk loading it takes less power to lift the weight of the aircraft. [1] The lower power required allows for a smaller propulsion system and reduces the fuel burn in hover. In addition, cyclic control of the rotor system generates significant control power which allows the aircraft to safely fly in close-proximity operations which required the ability to react to disturbances with quick and precise control inputs to minimize the resulting motion of the aircraft.

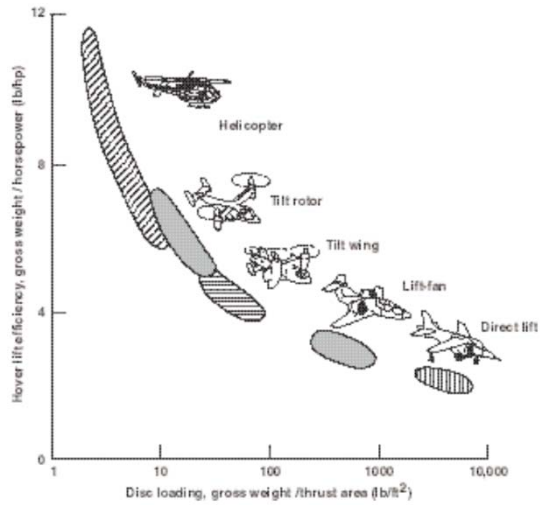


*Figure 1. Hover Efficiency vs. Disk Loading*

There are three primary advantages to Greased Lightning technology relative to conventional rotorcraft. The first is no speed limit due to retreating blade stall. To learn more about retreating blade stall refer to reference [2]. The second significant advantage over rotorcraft is improved aerodynamic efficiency. Typical fixed wing aircraft achieve a best lift to drag ratio of 14 to 20. Rotorcraft typically have an effective lift to drag ratio of 4 to 5.

$$Effective\ L/D = \frac{Weight\ of\ Aircraft * Cruise\ Velocity}{Power\ Required}$$

Note this equation can also be applied to a fixed wing aircraft and the result is equal to the aerodynamic lift to drag ratio. Aircraft with low effective lift to drag ratio, specifically rotorcraft, are limited in range and consume more energy to fly the mission. This leads to higher operating costs of the aircraft. The third shortcoming of rotorcraft is they have multiple single point of failure modes, for example the pitch links. Granted that with proper inspection and maintenance the likelihood of a pitch link failure is very low, but these inspection and maintenance requirements increase operating costs.

Fixed wing aircraft on the other hand have good cruise performance, but need long prepared runways or launch and recovery equipment to become "runway independent". This launch and recovery equipment imposes a significant logistical burden on the organization that is operating the aircraft. The Greased Lighting aircraft is designed to capitalize on new technologies available today to fly aircraft configurations that were previously not possible, thus enabling an aircraft to achieve performance capabilities that were also previously unachievable.

# 3 Key Technologies and Benefits

The two primary technologies that enable this aircraft design are distributed electric propulsion (DEP) and closed loop controls. Tilt wing VTOL aircraft are not new and have been investigated by multiple companies and government research programs. Refer to www.vtol.org/wheel for a list of historical piloted VTOL prototypes that have flown. Many of these aircraft flew safely for many years, but only the AV-8B, Yak-38, V-22 and F-35 have become operational aircraft. There are many reasons for the limited success of previous VTOL aircraft, but they fall into four main categories. First, the resulting useful load fraction of the aircraft was small because the cross shafting and other VTOL systems significantly increased the empty weight of the aircraft. Second, the Effective L/D of the aircraft is noticeable less than their fixed wing counter parts, and therefore overall performance suffers. Third, while these aircraft were flyable, their handling qualities were usually poor and required highly trained and skilled test pilots to safely operate. Additionally, in general many of these aircraft would be disturbed by wind gusts more than rotorcraft and thus had smaller allowable wind environment envelopes. Fourth, the inspection and maintenance requirements were large due to the numerous single points of failure. Considering these previous shortcomings, when new technology can be infused into products, it is worthwhile re-investigating concepts that were previously considered infeasible, or iterating from previous lessons into new concepts.

In addition to DEP being a propulsion technology, it is also an integration technology that enables aircraft to be designed in new ways. The primary benefit of DEP is to allow the aircraft designer to integrate the propulsion on the airframe in synergistic locations without the penalties associated with distributing combustion propulsion systems. Combustion propulsion, both turbine and reciprocating engines, achieve economies with scale. In general, the larger the combustion engine, the better its power to weight ratio and its efficiency. With electric motors, this sensitivity is greatly diminished. A small electric motor has similar power to weight ratio and efficiency as a larger electric motor of the same technology level. This enables the aircraft designer to integrate thrust into areas where drag is produced to achieve an improvement in system level performance. For example, assume propulsion was added concentric to the wing tip vortex where the propeller swirl and the wing tip vortex rotate opposite to each other. This results in improved overall system level performance of the aircraft with the same component (e.g., propeller) efficiency.

In the case of VTOL aircraft that require distribution of propulsion to control the aircraft, this distributed propulsion shows promise of reducing weight and maintenance of drive shafts and gearboxes, and potentially achieve a relaxed certification burden due to redundancy in the propulsion systems. This will improve the useful load of the aircraft. Additionally, due to the ability to highly distribute the propulsion, this allows two benefits. First, modulating the thrust of these distributed propulsors will generate greater moments on the aircraft enabling the aircraft to operate in higher gust environments. Second, the electric motors can be easily shut off and the blades folded to adjust the disk area for the current flight condition. A significant body of research has been applied to variable diameter rotors in order to adjust the disk area for the current flight condition. With DEP, this challenge is circumvented by shutting down motors and folding props to reduce disk area.

Closed loop control systems have advanced greatly from previous aircraft. The capability has increased dramatically and the cost has reduced dramatically. For the XC-142 program, there was a mechanical control allocation module that mixed pilot inputs to control surface outputs as a function of wing angle. Additionally there was no closed loop stability augmentation system on the aircraft either. Today there are multiple autopilots on the market that cost less than $200 that are capable of stabilizing an unstable aircraft and flying it on a fully automated mission without human input. The most popular of which is the Pixhawk [3].

# 4 Intent Behind Aircraft Design Decisions

The Greased Lightning design is unique in a number of ways. The unusual features of the design have a purpose that best capitalizes on state of the art technologies optimizing the aircraft for its design mission. The design reference mission of the aircraft is a 24 hour flight from vertical takeoff to vertical landing. Figure 2 illustrates the details of the sizing mission profile that the full scale GL-10 was designed for. It is important to note that this is a loiter dominated mission that the aircraft was designed for. So the design is optimized for lower wing loading, but the 100 knot cruise segment kept the wing loading at a reasonable level.

It is important to note that there are three different scale versions of GL-10. The full scale version was designed to fly the mission outlined in Figure 2. It had a 20 foot wingspan and 275 lb. maximum takeoff weight (MTOW) and it assumed 2020 technology levels for electric motors, batteries and structural materials. The next version of GL-10 was the final flight article, of which one aircraft was built at the 10 foot wingspan, 62 lb. MTOW and 50% scale. To keep the project in budget, it was decided that it was infeasible to build the 20 ft wingspan version with the resources available. Lastly, there was an even smaller version fabricated, named GLARF (Greased Lighting Almost Ready to Fly) for controls development work. There were 5 GLARF aircraft built and 3 were lost during the flight testing campaign. The GLARF aircraft were 7 foot wingspan, 25 lb. MTOW and 35% scale. Additionally there was a wind tunnel model that had a 5.85 foot wingspan at the 30% scale.

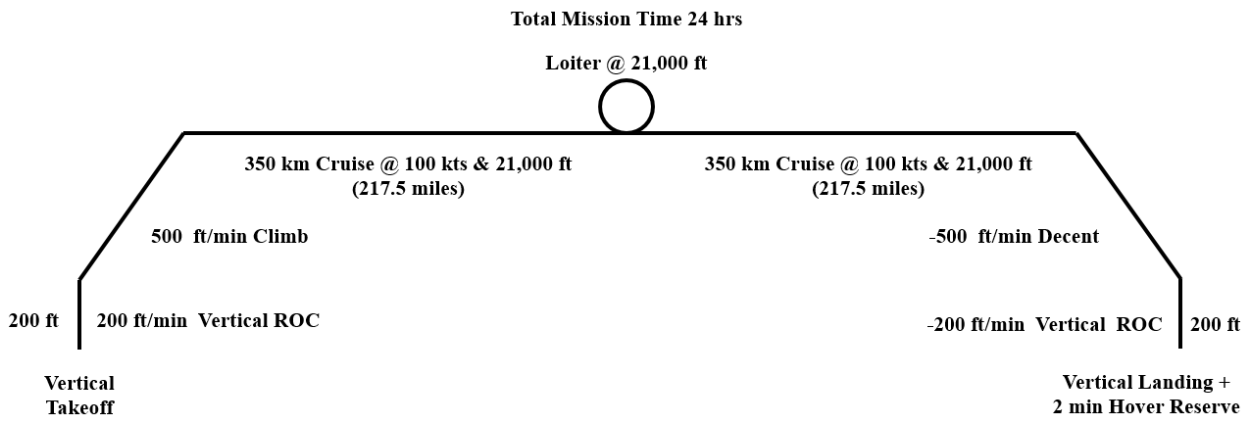


*Figure 2. GL-10 sizing mission profile.*

*Table 1. Sizes of Greased Lightning Models.*

| | Wind Tunnel Model | Foamie | GLARF | GL-10 | Full Scale Design |
|---|---|---|---|---|---|
| Scale | 28.125% | ~25% | 35% | 50% | 100% |
| Wing span (in) | 70.7 | ~72 | 87 | 124.8 | 249.6 |
| Wing Area (in2) | 361.2 | Not Recorded | 559 | 1141.7 | 4566.8 |
| Mean Chord (in) | 5.44 | Not Recorded | 6.7 | 9.67 | 19.34 |
| MTOW (lbs) | N/A | ~7 | 28 | 62 | 275 |

The first feature of the aircraft that is most unusual is the number of electric motors and propellers. In hovering flight, thrust must equal weight and in forward flight, thrust equals drag. Due to the aerodynamic efficiency of the aircraft in cruise configuration, the thrust required in loiter is approximately 6% of required hover thrust. As described above, having multiple redundant electric motors allows many of the motors to be shut down and their propellers folded while in cruise flight. This is useful because the disk loading in both hover and in forward flight is close to ideal to maximize propulsive efficiency. As a contrasting example, the V-22 Osprey's rotor diameter is a compromise between hover and cruise flight. In hover, the aircraft would benefit from an increased rotor diameter. In forward flight, the aircraft would benefit from reducing the rotor diameter. While not yet tested in flight for the GL-10, 8 of the 10 motors would be shut down and their propellers folded leaving only the wing tip motors operating in cruise. When a steeper climb gradient is required, a second pair of motors would be started to allow the aircraft to climb more steeply. The wing tip motors continue to operate at cruise and their propellers rotate opposite to the wing tip vortex taking advantage of that aero-propulsive benefit. [4] CFD analysis (full Navier-Stokes) of an isolated wing operating at the loiter condition of approximately CL=1.1 indicated an L/D improvement of 21.6% with the wing tip propellers installed, due to the location of the wing tip propellers' swirl roughly concentric to the wing tip vortices. In the GL-10 design, the total drag of the wing is approximately half of the whole aircraft drag. An L/D improvement of about 11% on the entire aircraft is expected at this flight condition. Lower gains are expected at lower CLs and higher aspect ratios.

The second unusual feature for an aircraft that operates well below transonic speed is the swept wing. Clearly, the wing sweep was not added to reduce compressibility drag, but to increase the lift to drag ratio (L/D) of the aircraft. In general, L/D has little sensitivity to wing sweep, but the GL-10 design has an

unusual constraint. As a VTOL aircraft, in hover, the centroid of the thrust of the 10 propellers must be centered on the center of gravity (CG). In the full scale design, the wing props are 1 foot forward of the CG and the tail props are 5.33 feet aft of the CG. Therefore to trim in hover the 8 wing props carry 84% of the weight of the aircraft and the tail props carry 16% of the weight of the aircraft. It was decided not to have an 80/20 thrust split (each propeller with equal thrust) to account for the failure of a tail motor. This thrust margin, in addition to a bus voltage increase, would allow one tail motor to generate sufficient thrust to trim the aircraft. With this thrust split and no sweep in the wing or tail, in wing borne flight, the wing would have to carry 84% of the weight of the aircraft and the tail 16%. Since the tail has worse span loading than the wing, its induced drag is greater per unit lift. Adding sweep to the wing shifts the aerodynamic center (AC) of the wing aft when in forward flight configuration in order to carry more of the weight of the aircraft on the wing. With a leading edge wing sweep of 30 degrees, 100% of the weight of the aircraft could be carried by the wing in forward flight while still maintaining the same thrust balance in hover. The challenge associated with a large wing sweep is the torque required to rotate the wing from forward flight to hover is great and requires a large actuator, thus extra weight. Therefore, a trade study was performed to determine the optimal wing sweep. The design settled on a 15 degree leading edge wing sweep with 93% of the weight of aircraft carried by the wing and 7% carried by the tail.

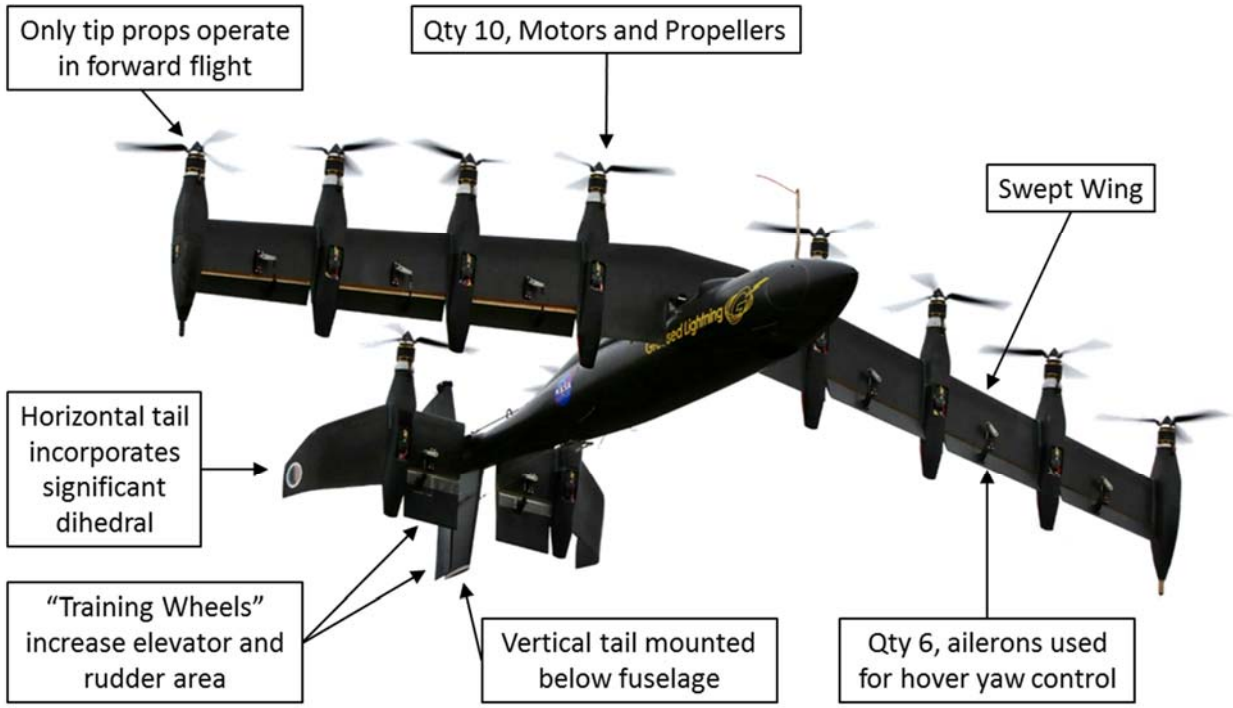


*Figure 3. An annotated picture of GL-10 approaching for a vertical landing.*

The vertical tail of the aircraft is mounted on the bottom of the fuselage. Since the aircraft is a VTOL and does not need to rotate for takeoff and landing, locating the vertical tail under the fuselage provides a convenient location to locate one of the landing skids. The lower vertical tail area was kept small and the rest of the vertical tail area at the tips of the horizontal tail to act as winglets because the horizontal tail carries 7% of the weight of the aircraft. It is also interesting to note that the total vertical tail area is significantly less than most other airplanes. This is because the control system modulates the thrust of the wing motors to provide additional yaw control power in forward flight. There is a segment of the

horizontal tail that incorporates dihedral because at the low speed end of the transition corridor, with the tail closer to hover configuration, the dihedral adds some "weather vane" stability to increase the directional stability of the aircraft at the low speed end of the transition corridor.

# 5 Flight Testing Campaign

## 5.1 Flight Test Objectives

One very unique aspect to this project was the willingness to accept risk in the planning of the project. The GL-10 project started as a reimbursable task. The external customer stated, "Swing for a grand slam or strike out trying. We already have a base hit solution." Another challenge associated with the project was the funding level. The whole 2 year project totaled approximately $1.8 million in full cost accounting. Referencing other flight projects of this scale, this was a low funding level. Because of the "grand slam" project goal and the low funding level, the project needed to accept many technical and schedule risks in order to have a chance of success. Some of the key risks were: 1) control system architecture and gains were developed during flight test, 2) the schedule had zero margin in order to fit within the first funding increment, 3) low cost COTS avionics were used in this phase of the flight testing, 4) majority of the components in the aircraft (e.g. motors, ESCs, servos, etc.) were also low cost COTS from the RC hobby industry.

The primary objective of this first phase of GL-10 flight testing was an existence proof. The project's aim was to demonstrate in flight that the vehicle could perform both outbound and inbound transitions, from hover to wing borne flight and from wing borne flight back to hover respectively, in a reliable and repeatable way. It is intended that the aircraft will have follow on flight testing phases that would utilize the aircraft as a platform to test additional research objectives. For example, it is intended to have more capable avionics integrated into the aircraft to enable the aircraft to perform autonomy research.

## 5.2 Approach to Flight Testing

Given the customer's acceptance of risk, the project still needed to plan a path of risk mitigation that lead to the statement of airworthiness to begin flight testing the aircraft. Since this is a new clean sheet aircraft design with no prior flight history to reference in the certification process, an incremental build up approach was utilized. Figure 4 depicts the phases of the flight testing campaign of the project to manage risk and maximize likelihood of successfully demonstrating transition in flight. The number on each cell depicts the order in which each phase was conducted. Tethered flights were conducted at NASA LaRC inside building 1299F and at the Gantry. These tethered flights had the aircraft tethered from above on a belay line so the aircraft was protected from impact with the ground. This tethered process allowed the project to tune the proportional integral derivative (PID) gains with the flight hardware while minimizing the risk to the flight hardware. The tether was attached to the aircraft through the CG to minimize the moments imparted to the aircraft by the tether. Knowledge gained from proceeding phases were used as the starting point for follow on phases.

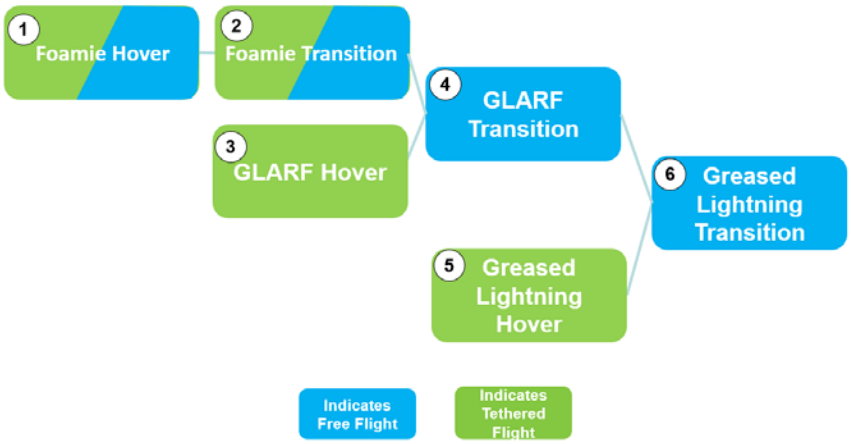


*Figure 4. Flight testing phases.*

The Foamie was a simple 6 lb. aircraft to test the functionality of the avionics hardware (KK2 Flight Controller) and flight software (OpenAeroVTOL). It was not intended to model GL-10, but only test the functionality of the flight software. The GLARF was utilized as a flying simulator of the GL-10. It served two primary roles: 1) To estimate PID feedback gains, 2) Determine the wing and tail rotation schedule through the transition corridor. Figure 5 shows photographs of the respective aircraft. This build up approach mitigated risk for the NASA LaRC Aviation Safety Review Board (ASRB). A flight safety release was issued one phase at a time. When all of the test objectives of one phase was finished, the project returned to the ASRB for the flight safety release for the next phase. This process allowed a compromise solution between minimizing risk and the aggressiveness of project goals.

*Figure 5. Photos of the Foamie, GLARF and GL-10 respectivly.*

Within a particular flight testing phase, the flight envelope was expanded incrementally. The flight would begin with the known condition, usually vertical takeoff and hover, move toward the edge of the currently tested envelope and back to the known condition for land. When aborts were required, the pilot immediately returned to the known condition. For example in phase 4 of the flight testing, GLARF would perform a vertical takeoff, rotate wing & tail ¼ of the way into the transition corridor, and then the

pilot would perform pitch doublets. A qualitative assessment was made of the: pitch stability, control power available and trim required, then the aircraft returned to hover and landed. Refer to Figure 6 for a flow chart depicting the process. Gains and schedules were adjusted as required and the next flight proceeded farther into the transition corridor. This incremental expansion minimized risk to the aircraft without having a full understanding of the flight dynamics before flight.

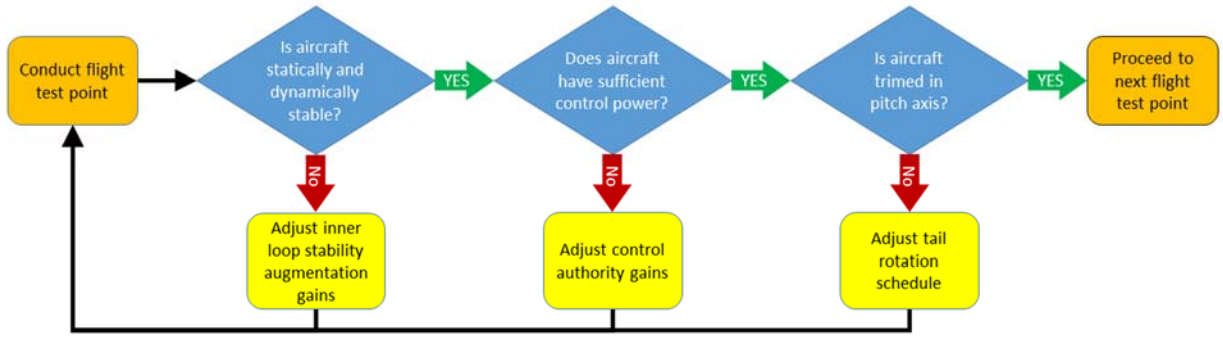


*Figure 6. Qualitative assesment process for envelope expansion of the GL-10 transition corridor.*

Much discussion and replanning went into the selection of the avionics. Since the aircraft is strongly unstable in hover and transition, stability augmentation was required as a flight critical system. Additionally, the number of control outputs is much too many for a human pilot to command. The project utilized a commercial off the shelf (COTS) controller to accomplish the initial demonstration of feasibility flight testing. To mitigate risks of poor quality control in the manufacturing of these avionics boards, each board was serialized and tested in flight on the GLARF before being used the GL-10 aircraft. When the aircraft's role changes from being a demonstrator to a technology test bed for follow on research, more capable custom avionics designed by NASA LaRC will be installed. These custom avionics will enable autonomy and acoustic research by incorporating more powerful processers, interfaces to more sensors, and ability to individually control each motor independently to tailor the acoustic signature given off by the aircraft.

The selected COTS controller for this first phase of testing was the KK2 board distributed by HobbyKing. [5] The selected software to run on the avionics is OpenAeroVTOL. [6] This is open source software designed to provide stability augumentation and control allocation to transitioning VTOL model aircraft. This software provided the minimun set of features required to fly the GL-10 to demonstrate that the aircraft can fly and transition between hover and forward flight and back again. To mitigate the risks of bugs in the open source software, software version control procedures were implimented. Software versions were first flight tested on GLARFs before being utilized in GL-10.

Another unique approach to the flight testing program was the use of additional horizontal and vertical tail area, affectionately called "training wheels" by the project, refer to Figure 7. Since the aircraft is unstable in hover and transition, the aircraft required a flight critical control system. Given that the flight critical control system is already on the aircraft, the longitudinal and directional static stability was significantly reduced to reduce the weight and drag of additional tail area. Note, the tails and control effectors were still sized to meet the control moments required. The horizontal tail is all moving and differential thrust of wing tip props provides significant yaw control power in forward flight. The design also incorporated small elevators and a small rudder to provide some high bandwidth control authority because the frequency response of the all moving tail and differential thrust was slower than ideal.

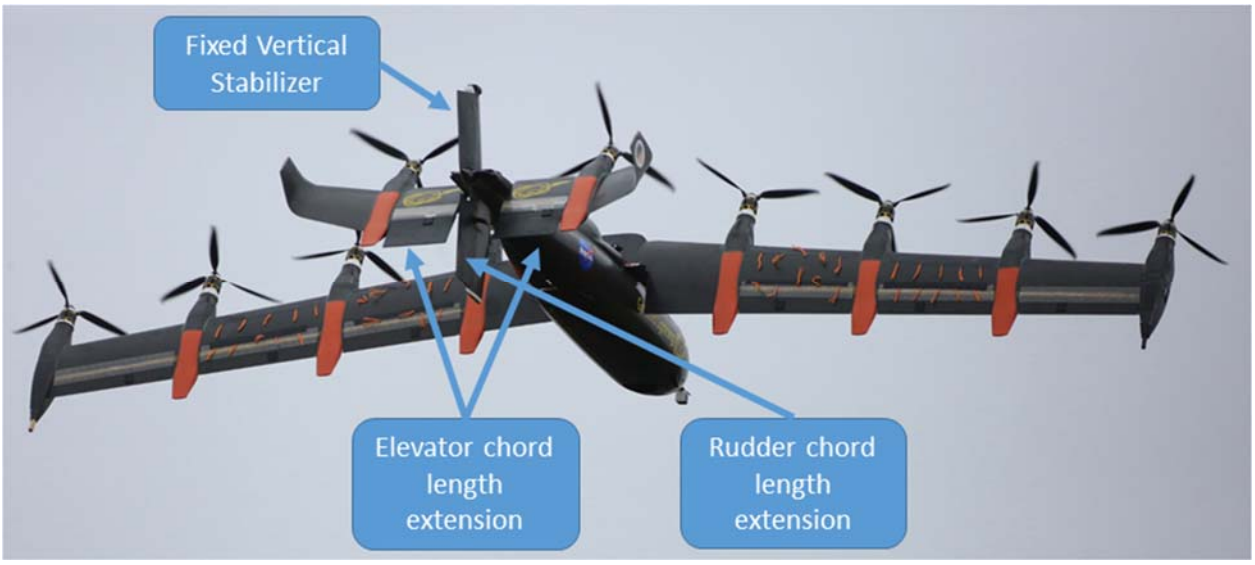


*Figure 7. GL-10 "Training Wheels" used in early flight testing phases.*

During the initial flights of both the GLARF and GL-10 flights extra tail area was scabbed on to the existing tails to increase the longitudinal and directional stability of the aircraft to be equivalent to conventional airplanes. As the flight envelope was expanded, the “training wheels” were incrementally reduced in size.

Like many other research aircraft, prior to the first flight of the day, an extensive preflight was performed. The operations procedures document topics ranging from meteorological go/no-go criteria that is approved by the ASRB to emergency procedures for the aircraft. The checklist, to be completed prior to first flight of the day, includes topics ranging from structural components that weaken with flight time to avionics functionality checks. The inspections took approximately 1 hour to complete each morning and they were signed by the test engineer to document that the inspections were properly completed in the event of an accident investigation.

While the GL-10 aircraft is a very unique aircraft design, the approach to its flight testing was conventional. The project utilized avionics that are lower cost, lower quality and readily available. To have reasonable trust in the avionics before flying the high replacement cost (~$300k) GL-10, the flight test campaign followed a buildup method to gain trust in the avionics. Each aircraft flown in the campaign utilized a method to incrementally expand the flight envelope. This approach allowed the project to have a reasonable chance of success while staying within our highly limiting resource constraints.

## 5.3 Results Generated in Flight

The flight testing phase that is the topic of this paper focused on envelop expansion through the transition corridor of the GL-10 aircraft. Due to funding limitations, once this objective was accomplished, this phase of flight testing ended. Therefore, very little performance testing and system identification testing was accomplished, but such testing is planned for future flight testing phases of the GL-10 aircraft.

Previous tilt wing aircraft had transition corridors that constrained the wing to remain below its stall angle of attack (AoA). At higher wing angles, the propellers are turning the flow such that the local flow velocity is still approaching the leading edge of the wing. The advantage of attached flow over the wing

in transition is the flight dynamics are linear, therefore making it easier for the pilot to fly the aircraft. With smaller scale aircraft, the resulting induced velocity through the propellers is less and therefore there is less flow turning. The upper surface of the wing was tufted and a camera was installed on the vertical tail to record when and where the airflow separates. Due to the lower induced velocity through the propellers, it can been seen when the separation boundary is reached. During the conceptual design of the GL-10 it was also assumed that the GL-10 would be operated in a similar way, with wing AoAs below stall AoA. This would be accomplished with a zoom maneuver. Figure 8 depicts this zoom maneuver. By flying such a trajectory, the wing angle of attack will always be below stall and thus reducing the need of the propellers to turn the flow.

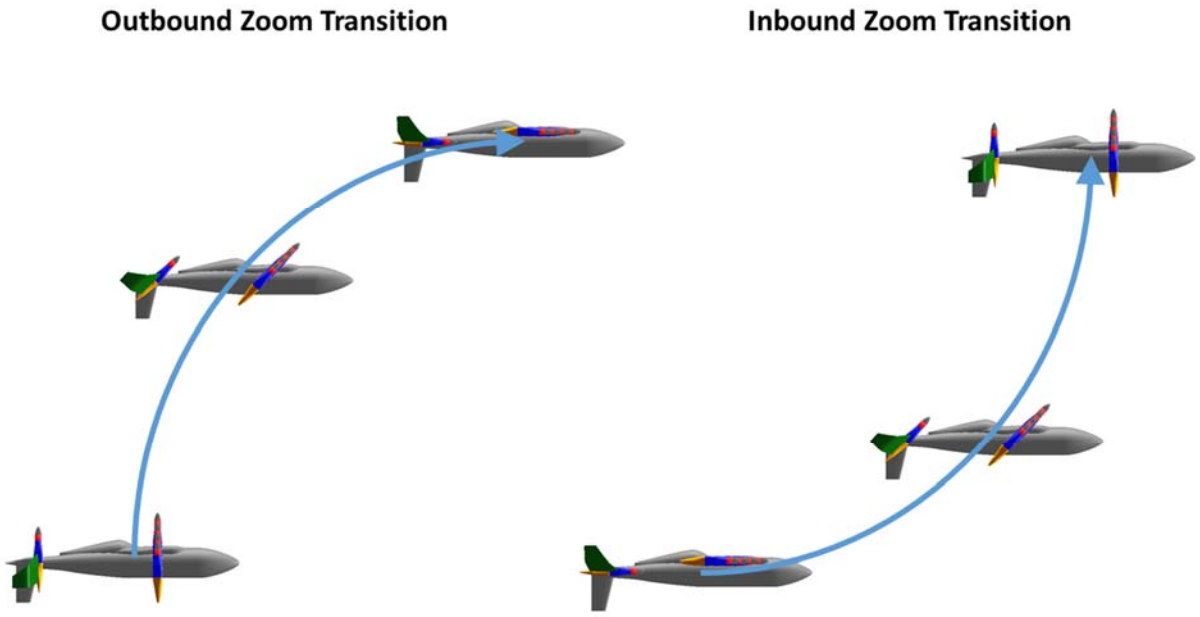


*Figure 8. Zoom Transition Profile.*

It was quickly found in flight testing of the GLARF aircraft that the zoom transition maneuver would be impractical. There are two primary reasons that this procedure became impractical. First, the aircraft was flown with a remote pilot, with the pilot flying the aircraft by looking at it from the ground (third person prospective). While performing this maneuver, the aircraft would rapidly get too far away for the pilot to see clearly. If resources were available to fly the aircraft autonomously and/or fly the aircraft with a first person view (FPV) live telemetered video feed, this challenge would have been mitigated. The second reason is the aircraft would build/reduce airspeed much more quickly than the wing can rotate. If a faster and/or more powerful wing tilt actuator were installed, it would have caused a noticeable increase in the empty weight of the aircraft. At this point it was decided to investigate performing transitions at post stall AoA.

As the team began to investigate the possibility of post stall AoA transitions, it was found that the unsteady and destabilizing yawing and rolling moments generated by the stalled wing were less than the control power the vehicle can generate. Due to the distributed electric propulsion (DEP) design of the aircraft, utilizing differential throttle of the motors can generate large pitch and rolling moments on the

aircraft. It was found in this phase of flight testing that the moments the aircraft can generate is greater than the unsteady moments generated by the stalled wing. This then presented a closed loop gain tuning challenge.

During this stage of the flight testing, the flight dynamics mid transition were simply unsatisfactory. In a mid-transition configuration, the aircraft would perform a "back stroke" type oscillation with a coupling between the roll and yaw axes. As the controller would provide a command to pick up the low wing, it would throttle up the motors and deflect the ailerons trailing edge down on the low wing and the opposite command on the high wing. The result was the low wing would move forward as it moved up which would increase its dynamic pressure and increase its lift on that side to bring up the wing as the aircraft rolled through wings level at increasing sideslip. The controller would then reduce throttles on that side which reduced the blowing and the flow turning and the drag of the wing on that side became greater which pulled that wing back and it would fall. At which point the oscillation would repeat. It was found that the effectiveness of the differential throttle was significantly greater than the effectiveness of the ailerons. The fix to this "back stroke" type oscillation was to reduce the gains of the throttles and increase the gains of the ailerons such that when the controller commanded the low wing to come up it generated a rolling moment with zero yawing moment and would not induce sideslip on the aircraft.

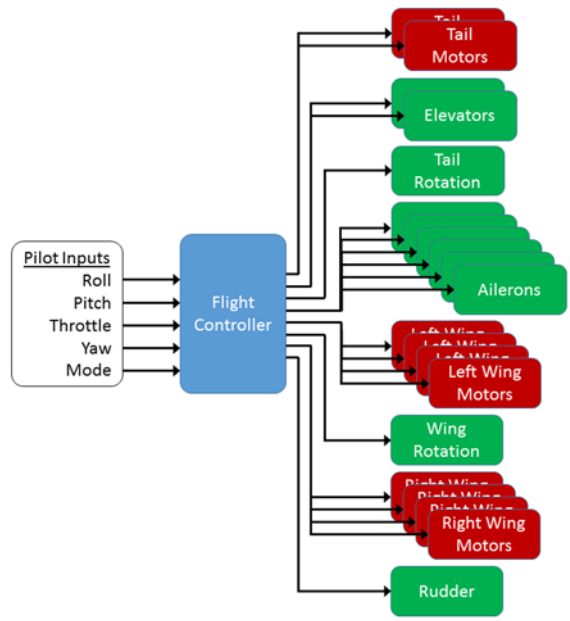


*Figure 9. Basic Flight Controls Wiring Schematic.*

Figure 9 shows the basic flight controls wiring schematic. The flight controller (KK2 avionics with OpenAeroVTOL software) is responsible for three functions. First function is stability augmentation. There are Micro-electromechanical systems (MEMS) included in the avionics which provide angles and angular rates. These sensors feed simple proportional integral derivative (PID) feedback loops to provide the stability augmentation. Second is the control allocation / transition mixing. In hover vs. in forward flight the control effectors are used for different functions. Third is the scheduling of the transition. This schedule was open loop as a function of time. Where the pilot would move the mode selector switch and the wing and tail would rotate along with the control mixing reconfiguring. The wing and tail rotation would follow a piecewise linear open loop schedule with time and the control mixing was simply a linear interpolation between hover and forward flight as a function of time. Table 2 lists the control allocation for the desired force and moment commands as a function of flight mode.

| | Roll | Pitch | Throttle | Yaw |
|---|---|---|---|---|
| **Hover** | Right vs. Left Wing Motors | Wing Motors vs. Tail Motors | All Motors | Ailerons |

| | | | | |
|---|---|---|---|---|
| **Forward Flight** | Ailerons | Tail Rotation and Elevators | All Motors | Right vs. Left Wing Motors and Rudder |

*Table 2. Control allocation and mixing in hover vs. forward flight.*

Figure 10 depicts the transition corridor for the GL-10 aircraft. The transition corridor is bounded by a number of constraints. The first point to discuss is the wing borne flight stall speed. This point is what is considered stall speed for the conventional airplane being defined as the airspeed by which the maximum possible lift of the wing is equal to the weight of the aircraft. There is a lower bound to the transition corridor that comes through this point. With higher wing angles, the thrust of the props provide powered lift. The lower red curve is an approximate trace of the boundary where the aircraft can no longer provide sufficient vertical force to lift the weight of the aircraft. The next constraint on the transition corridor is the design load case for the wing tilt actuator torque. Above this airspeed, the torque on the wing tilt actuator is greater than the design load. It is important to note that once the wing has transited all the way to forward flight configuration, the airspeed may safely exceed 70 ft/s (41.5 kts or 21.3 m/s) because the wing rests in a saddle when in forward flight configuration. Once the wing is resting against the saddle, the load path no longer passes through the wing tilt actuator. Next there is a triangular area outlined by the yellow boundary. At flight conditions above this yellow line the horizontal component of thrust is less than the drag of the aircraft. Meaning the aircraft is unable to accelerate.

The blue dots in Figure 10 are traces from 10 different flights. It can be seen in the figure, the testing started in hover. Then the next flight proceeded to a ~63 degree wing angle where it performed multiple pitch doublets, with airspeed varying at constant wing angle, to check pitch control power, trim, static stability and damping. The flight returned to hover and landed. The 3$^{rd}$ flight plotted performed hovering takeoff, transition to ~49 degree wing angle, again checking pitch control power, trim, static stability and damping, returned to hover and landed. The transition corridor envelope was incrementally expanded in this manner. The intent behind this procedure was to start from a known condition, move to the unknown condition and return to the known flight condition. It is also interesting to note that many of the traces were outside the bounds of the transition corridor. This is because the aircraft was not at a steady state condition. The traces that drop below the lower bound were during outbound transitions with the vehicle at less than 1 G. The traces that exceed the upper bound were all inbound transitions with airspeed bleeding off rapidly. It is also interesting to note that 2 of the flights plotted exceed the wing tilt actuator load case. It was difficult for the pilot who was hand flying the aircraft from a 3$^{rd}$ person prospective to get on target airspeed. He was assisted by near real time telemetry of airspeed, but it was still a challenging task. For reasons like these, it is important to include margin in the design. The wing tilt actuator was designed with a 50% margin on the load case.

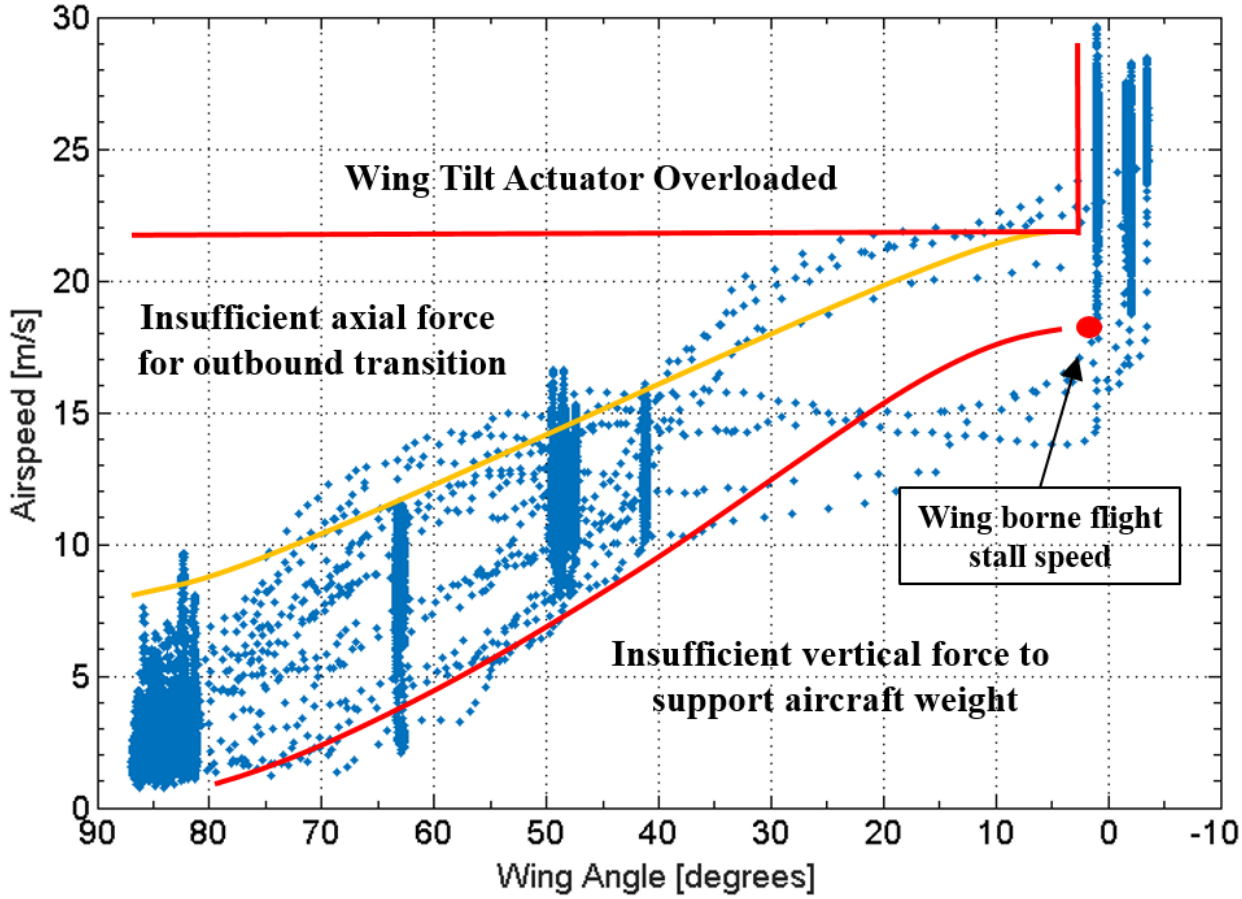


*Figure 10. GL-10 Transiton Corridor Plot.*

To record the data in Figure 10Figure 2 and the majority of GL-10 flights a simplistic data acquisition system was installed in the aircraft using a Pixhawk autopilot [3]. The Pixhawk was used to log all of its internal sensor data and two external sensors were also installed. The first sensor was pitot/static source that is Pixhawk compatible to measure airspeed. Second, an analogue potentiometer was installed to measure the wing's angle. In addition, the pilot inputs to the flight controller were logged using the Pixhawk.

Another unique result found in flight was the tail rotation schedule. With the control software architecture of OpenAeroVTOL, there is no ability to "close the loop" on pitch trim. The software required an open loop tail rotation schedule as a function of time. Likewise, the wing required an open loop wing rotation schedule as a function of time. Therefore, the tail rotation schedule can effectively be a function of wing angle. At the beginning of the GLARF testing, the team started with a 1:1 schedule, where the tail angle was equal to the wing angle. It was found that this resulted in the pilot needing to nearly saturate his pitch up control power. The rotation schedule was adjusted such that the tail rotated toward forward flight ahead of wing in outbound transition and lagged behind the wing on inbound transitions to minimize the pitch inputs required of the pilot. The reason is the loading of the wing is greater than the loading of the tail such that the wing needs to be rotated farther toward hover than the tail for a given point in the transition corridor, thus the nose up moment generated by lift on the wing is balanced by the nose down moment generated by lift on the tail.

Flight testing also demonstrated that hover yaw control was inadequate. Like the previous tilt wing X-planes, the yaw axis of the aircraft in hover is commanded via slipstream control of the propellers blowing over the ailerons. Due to the reduced induced velocity of the propellers relative to the previous tilt wing X-planes, there is less dynamic pressure for the ailerons to utilize. Additionally, due to the fact of the aircraft being a tilt wing, gusts can generate large yawing moments on the aircraft because of the projected area due to the wing being vertical. It was found in flight testing that an operational wind limit needed to be imposed on the operations of the aircraft to limit steady state wind speed to less than 10 mph and the difference between peak gusts and steady state to be less than 4 mph. For example if the steady state wind speed was 6 mph and in the gusts the wind was 12 mph, we would not operate the aircraft.

An additional yaw control issue was uncovered. This issue manifested itself when the aircraft was performing vertical descents. At this condition the AoA, relative to the fuselage is -90 degrees (wind coming up toward the belly of the aircraft). As the vertical speed of the aircraft began to approach the propeller induced velocity, the freestream velocity would cancel with the propeller slipstream and the net result was negligible dynamic pressure for the ailerons to generate moments. It can be clearly seen using the onboard video footage the aircraft entering this condition and the control surfaces saturate with little ability to yaw the aircraft which causes the yaw axis to become unstable and the aircraft enters an oscillation. Fortunately, at this condition, the pitch and roll control power is more than sufficient, so the aircraft would not depart from controlled flight. The yaw oscillation is arrested by throttling up, which increases the dynamic pressure for the ailerons and arrests the rate of descent. The operational fix to this issue was to simply avoid this flight condition.

Another result generated in flight was new operational procedures in the operation of the aircraft. During takeoff and outbound transition, the initial operational procedure was to climb to a safe altitude in hover and then as quickly as possible pass through the transition corridor as quickly as possible into wing borne flight. Note, safe altitude was defined as two mistakes high, which was usually ~300 ft above ground level (AGL). Where the pilot has sufficient altitude to make a mistake, then make a second mistake trying to recover, and still have the altitude where correct inputs would recover the aircraft before impacting terrain. Climbing in hover mode to this safe altitude was time intensive and energy intensive. Due to the high power required in hover, spending significant time in hover would leave limited energy available for wing borne flight. Once the control system gains were sufficiently tuned for the aircraft to be well behaved in mid transition configuration, it was decided that immediately after the vertical takeoff to transition to mid transition configuration. This provided two benefits. First, even though at mid transition the wing is completely stalled, the power required to fly at this condition is still less than the power required for hover. This allowed the aircraft to climb and build airspeed more quickly, which allowed the aircraft to get to its safe altitude in less time and consumed less of the battery energy. The second benefit of this operational procedure was in mid transition configuration, with typical airspeeds of ~25 kts (~13 m/s), the aircraft was significantly less disturbed by gusts as compared to when in hover mode.

## 5.4 Summary of GL-10 Flight Incident

The GL-10 UAV with the 10-ft wingspan was flown September 1, 2015, and a mishap occurred which caused damage to the airframe during an acoustic research flight test at Fort A.P. Hill in Virginia. Much of the damage happened while retrieving the vehicle from a very tall pine tree. A mishap report was generated, “Report of Findings for the GL-10 UAS Type D Mishap of September 1, 2015”, and a presentation was provided to the Center via a quarterly UAV working group. The presentation focused on: findings with causes, contributing factors, failed barriers, and lessons learned.

Some of the causes for the mishap include: departure of controlled flight and the loss of an access hatch which impacted a tail motor propeller, loss of remote controlled link due to interference by shadowing of the conductive graphite epoxy airframe structure, insufficient positive locking fasteners for airframe parts, and project structure/quality assurance processes. If the team had more time and funding there could have been more support to enable proper handling of the needed processes. The return to flight of this UAV will review the lessons learned to increase the likelihood of success.

## 5.5 Lessons Learned

In phase 4 of the flight testing campaign, refer to Figure 4 (GLARF Transition Flight Testing), three of the five GLARF aircraft were lost. The following outlines the three GLARF accidents.

Using video records of the flight of the first GLARF crash, it could be seen that while in hover, the horizontal tail suddenly rotated toward forward flight and the aircraft aggressively pitched up and departed from controlled flight. Upon inspection of the aircraft it was found the linkage between the servo and the horizontal tail has been separated. This combined with the video evidence of the horizontal tail in its un-commanded orientation while still in flight, was thus wrongly deduced this was the cause of the crash.

In the second GLARF crash, the aircraft was entering into the transition corridor and it aggressively rolled left, departed from controlled flight and stopped responding to pilot input. No definitive evidence was found. The kill switch was found with thermal damage and its contacts had partially melted. A kill switch was installed in the aircraft because the batteries were installed inside the aircraft without quick access to them. The kill switch was on the exterior of the aircraft in order to quickly remove power to the electrical bus. It was wrongly deduced the kill switch was the cause of the crash and the kill switches were removed from the rest of the GLARF aircraft to remove this possible failure mode.

When the third GLARF crashed, the aircraft had just performed a vertical takeoff and when only a few feet off the ground performed a full back flip and impacted the ground in level pitch and roll attitude. Other than damage clearly caused by the hard landing, nothing was out of place. It was determined from video evidence that the horizontal tail suddenly rotated to forward flight orientation causing the back flip. What was also found from video evidence that 4 seconds after the tail rotated and ~2 seconds after impact, the horizontal tail returned to its proper orientation. Thus when we walked up to the aircraft nothing was out of place. The connection was made that the startup time of the avionics is ~4 seconds. When the avionics are restarting, there are no outputs from the avionics and thus when free to rotate the tail will rotate to forward flight orientation. It was finally discovered that the avionics bus voltage was dropping below 4.6 volts which triggers a restart of the avionics. This failure mode was the root cause of all three crashes and very intermittent and many successful flights were conducted between crashes. Using an oscilloscope, it was determined that the nose wheel servo would intermittently pull down the 5.1 volt bus 0.3 volts. Additionally, when at full power, the bus voltage was pulled down 0.2 volts. The combination of the nose wheel servo noise and being at high power would trigger the restart of the avionics. The fix was all servos were placed on a separate bus from the avionics and the project never again had an issue with avionics brown outs. While these crashes lead to many schedule delays, it was good this issue was resolved on the less expensive GLARF aircraft before flight testing of GL-10 commenced.

In phase 6 of the flight testing campaign, refer to Figure 4 (Greased Lightning Transition Flight Testing), as previously mentioned, “training wheels” were used to increase the longitudinal and directional stability

of the aircraft during the envelope expansion phase of the flight testing. It was found, via flight testing that the directional stability was sufficient with the “training wheels” removed. In successive flights, the “training wheels” were reduced in size until they were removed all together. Using differential thrust to control the yaw axis provided adequate artificial stability to have sufficient handling qualities. If the aircraft were to fly faster, and/or the vertical tail area was further reduced, it is possible that differential thrust of the motors would not have sufficient bandwidth to safely fly the aircraft.

It was found in flight testing, that the longitudinal axis did not have sufficient handling qualities with the training wheels removed. Only 1 flight was conducted with the horizontal tail “training wheels” removed. During the outbound transition, the aircraft went into a statically stable dynamically unstable pitch oscillation, where the amplitude of each oscillation grew larger. From the data logs, it was found that pitch angle surpassed +/- 60 degrees. The oscillation grew very quickly and the flight crew aborted back to the known condition (hover in this case) and landed the aircraft without further incident. It was decided to reinstall the horizontal tail “training wheels” and not investigate the flight condition further because the project was on its final funded deployment. The horizontal tail “training wheels” were left on for the demonstration flights and the remainder of the project in order to maintain satisfactory handling qualities of the longitudinal axis during transition. Cooper-Harper handling quality ratings were not assigned after flights because the control gains were not optimized to improve handling qualities. In general when this paper refers to sufficient handling qualities it refers to a Cooper-Harper rating of 5 or better.

The final primary lesson learned from this flight project is in regard to slipstream control. All of the previous VTOL tilt-wing aircraft utilized slipstream control to control the yaw axis of the aircraft in hover. The prop wash would blow over the wing and as the ailerons were deflected with the wing in hover orientation, yawing moments are generated. As previously stated, in the flight testing of Greased Lightning it was found that the yawing moments that could be generated in this manner is less than required to react to disturbances imparted onto the aircraft by gusts. There are two reasons that Greased Lightning had less yaw control power in hover relative to the previous tilt-wing designs. The first reason is because of its small scale, the disk loading of the propellers is significantly lower which results in a lower induced velocity blowing across the wing. Due to this lower dynamic pressure for the ailerons to operate in, there is reduced control power. The second reason, also because of its smaller scale, is the wing loading of the aircraft is much less than previous tilt-wing aircraft. This lower wing loading means there is more wing area presented to the gust relative to the mass/inertia of the aircraft and thus is more greatly disturbed by gusts relative to larger scale aircraft. It should also be noted that the previous tilt-wing aircraft also had operational wind limitations. One of the hard landing in the XC-142 program was because of saturating the control power while attempting a cross wind landing. This factor was anticipated during the conceptual design of the aircraft. Relative to historical aircraft designs, the aileron area is significantly greater than other aircraft. Most airplanes have ailerons that are ~30% span and 10% to 15% chord. The ailerons on Greased Lightning are 30% chord and full span. For the design of future VTOL aircraft of the small UAS scale, even with larger ailerons, do not rely on slipstream control for the low speed control of the aircraft.

# 6 Conclusions

It has been demonstrated, via flight test, that it is possible for the Greased Lightning design, that is both vertical takeoff and landing (VTOL) and achieves excellent lift to drag ratio, to safely and repeatable transition into cruise efficient wing born flight. There are two unique aspects accomplished in this program. First, while not formally verified, the Greased Lightning is believed to have set the record for the highest lift to drag ratio VTOL aircraft that has flown and transitioned. Second, the aircraft successfully operated at post stall angles of attack while conducting outbound and inbound transitions. This was the first demonstration in flight for a VTOL aircraft. In addition, this demonstration has been accomplished with a flight article with appropriate dynamic scaling relative to the full scale aircraft. For example, if the thrust to weight ratio was higher and the wing and disk loading was low, it would be easier for the aircraft to perform the transitions.

With the exception of yaw control power in hover and in the low speed end of the transition corridor, this aircraft design has sufficient control power to robustly handle disturbances throughout the transition corridor. Many previous VTOL aircraft had limited control power and thus could not be operated in challenging wind environments and had very limited allowable CG envelopes.

The ability to combine: cruise efficiency of a fixed wing aircraft, resilient to any motor failing, low noise, true VTOL capability, will enable new aviation markets. The Greased Lightning design is useful at scales ranging from a ~55 lb. MTOW aircraft to a ~3000 lb. MTOW aircraft carrying 4 people. The useful markets range from surveillance/data acquisition roles to package delivery to on demand personal aerial transportation.

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**14. ABSTRACT**
Greased Lightning (GL-10) is an aircraft configuration that combines the characteristics of a cruise efficient airplane with the ability to perform vertical takeoff and landing (VTOL). This aircraft has been designed, fabricated and flight tested at the small unmanned aerial system (UAS) scale. This technical memorandum will document the procedures and findings of the flight test experiments. The GL-10 design utilized two key technologies to enable this unique aircraft design; namely, distributed electric propulsion (DEP) and inexpensive closed loop controllers. These technologies enabled the flight of this inherently unstable aircraft. Overall it has been determined thru flight test that a design that leverages these new technologies can yield a useful VTOL cruise efficient aircraft.

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