Maturation of the Mono Tiltrotor (MTR) Aircraft Architecture, and Its Application to Heavy Lift and Other Emerging Needs

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Abstract

The Mono Tiltrotor (MTR) is a proposed, innovative heavy-lift rotorcraft architecture. The capabilities of the MTR are predicated on the combination of an advanced coaxial rotor system and sophisticated kinematics that morph the aircraft topology for efficient flight over the entire operational envelope. The MTR rotorcraft integrates a coaxial rotor, a folding lifting wing system, a lightweight airframe and an efficient cargo handling system that is capable of rapidly and economically transporting a variety of mission tailored payloads. This paper reports on the innovative steps taken to mature the MTR aircraft architecture, a summary of MTR aircraft concepts suitable for emerging military needs, and progress in developing MTR knowledge, including preliminary design and wind tunnel testing activities.

Introduction

A simple thought has generated into the fully developed Mono Tiltrotor (MTR) aircraft architecture, which is now the subject of funded research, design, and test activities. Legacy aircraft concepts have their center of lift, thrust, and the payload at essentially the same location for stable flight. This collocation of aerodynamic forces at the payload is a central dilemma for low disk loading, high speed VTOL concepts. Suboptimal compromises to accommodate this dilemma are to have wingtip mounted tilting proprotors, or auxiliary propulsion while offloading an edgewise rotor. The simple thought is to remove this dilemma by suspending the payload about the pitch axis of the aircraft.

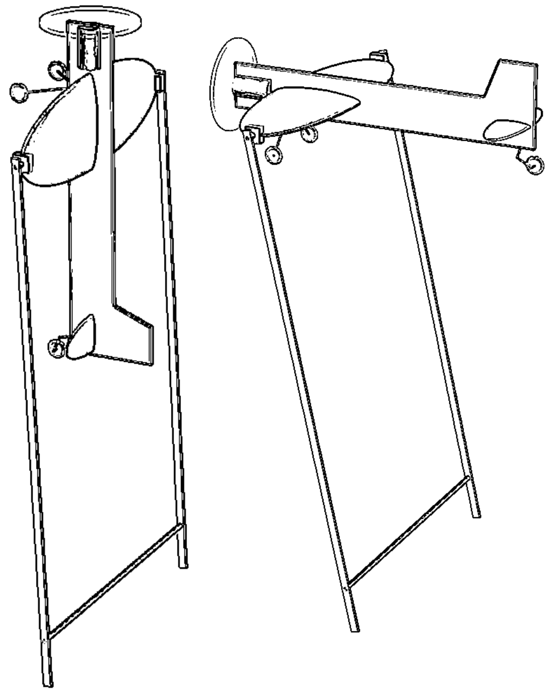

Figure 1: Suspending a payload about the pitch axis of an aircraft.

A hypothesis was developed that transition between vertical and horizontal flight becomes stable by suspending a load about the pitch axis. An inexpensive free-flight test of this hypothesis was performed based on an off-the-shelf remote control airplane having a static thrust greater than gross weight. The airplane was modified by suspending a load from a freely rotating shaft mounted at the wing quarter chord (Figure 1). Indeed, the suspension structure and load tended to maintain a fixed orientation with respect to the earth's inertial axes, while the airplane pitched between vertical and horizontal slow speed flight. The three dimensional problem of stable conversion between vertical and horizontal flight was constrained by the suspended load into a simpler two dimensional problem. The suspended load had no effect on airplane pitch stability and control, yet dramatically increased stability about all other axes. Methods for replicating this test are found in U.S. Patent 6,783,096.

This minor breakthrough opened a virgin design space. The "airplane" of this simple experiment has the

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architectural potential for combining a large diameter, low disk loading rotor with a high aspect ratio, fixed planar wing, in a structurally efficient system. The suspended "payload" has the architectural potential to have a shape, size, and design independent from the "airplane". By a process of accommodating real physical and operational constraints, this simple test configuration evolved into the scalable MTR architecture, and a series of MTR conceptual designs. The generic specification of the MTR aircraft architecture is provided in U.S. Patent 6,845,939.

Baldwin Technology Company (BTC) is a corporate entity dedicated to maturing the MTR. To expedite knowledge development and dissemination, all work is performed in a collaborative, unlimited data rights environment, with results published and communicated to the rotorcraft community in Government reports, conference papers, and over the Internet. An MTR Research and Development (R&D) Team composed of World Class rotorcraft institutions is under contract to BTC for MTR analysis, design, and testing. This core team is supplemented by individuals having unique and applicable rotorcraft industry expertise. We welcome all participation from the rotorcraft industry in developing this body of knowledge.

Concept Overview

The initial premise of this virgin design space was that a conventional, fixed wing, propeller driven aircraft offered efficient cruise performance, and efficient hover could be achieved by replacing the airplane propeller with a low disk loading rotor. A notional aircraft concept based on this initial premise was gradually adjusted to accommodate real physical and operation constraints (Figure 2). The MTR aircraft architecture became mature when the last identified constraint was accommodated. Subsequent to architecture maturation, conceptual design studies predicted breakthrough economic value and operational capabilities, and now preliminary design and testing activities are revealing practical technical capabilities.

Ideal Lift Unit

Starting from the premise of a fixed wing airplane having a single, large diameter proprotor and a pitch axis suspended load, the creative goal was to arrive at a practical aircraft configuration suitable for all flight modes without adding any further structural weight. If successful, the vehicle structural weight would be similar to that of a conventional crane helicopter, with the added incremental weight of the fixed wing. Cruise performance would be similar to a turboprop airplane, but with structural efficiency (or ratio of structural weight to gross weight) similar to a helicopter.

An initial obvious physical constraint is that a single rotor has unbalanced torque. The solution was to have a coaxial rotor, capitalizing on the rotorcraft industry's experience with coaxial helicopters (e.g. Kamov's family of coaxial helicopters, Sikorsky's Advancing Blade Concept, and Eagle Aviation's family of coaxial UAVs). It was presumed that a torque balanced, low disk loading, coaxial proprotor could have both a good hovering figure of merit and good airplane mode propulsive efficiency. This presumption was subsequently proven valid though aerodynamic analysis, as will be discussed in the Section on Work Underway, below.

This initial coaxial airplane configuration was then analyzed as a collection of subsystems. As a first approximation, the center of mass of the airplane itself was located at the rotor gearbox, with the fixed wing's center of lift positioned immediately above the gearbox. This arrangement is not surprising in that gearboxes tend be the heaviest component of helicopters, and tend to be located at a helicopter's center of mass. As a result, the pitch axis of this airplane passes through the gearbox, with the structurally advantageous consequence that the suspension structure can be pinned to the gearbox.

The hover mode of flight was then examined, with the load suspended from the coaxial gearbox. One immediate observation was that the tailboom and the suspension structure prevented the "coaxial crane helicopter" from landing. It was decided that both the upper end of the tailboom and the lower end of the suspension structure needed the ability to freely rotate in the pitch plane in hover mode, thus allowing the "coaxial crane helicopter" to land. A refinement was then added, where the tailboom and suspension structure have equivalent lengths and the tailboom's lower end is latched to the payload for increased compressive strength between the gearbox and the payload. Thus, the tailboom and suspension structure form a parallelogram in the pitch plane to assist in guiding the "coaxial crane helicopter" between rest mode and hover mode.

Hover gust loads became the next area to examine. Hover gust loads occur when the large vertical mass flow of a rotor wake combines with horizontal gusts to form a high angle of attack on a wake aligned fixed wing, resulting in large, instantaneous, unpredictable, horizontal loads. Hover gust loads could possibly be controlled by adding lift defeating spoilers to the fixed wing, and this possibility is still worth examining. A more certain solution to hover gust loads is to have left and right folding wing panels, such that the wing panels drop freely to the sides of the tailboom with their span aligned to the rotor wake in hover. Gust loading on the wing panels is then limited to small normal forces at their centroid, with moments absorbed by the freely rotating wing panel, and forces transmitted to the aircraft at the wing panel root, near the gearbox.

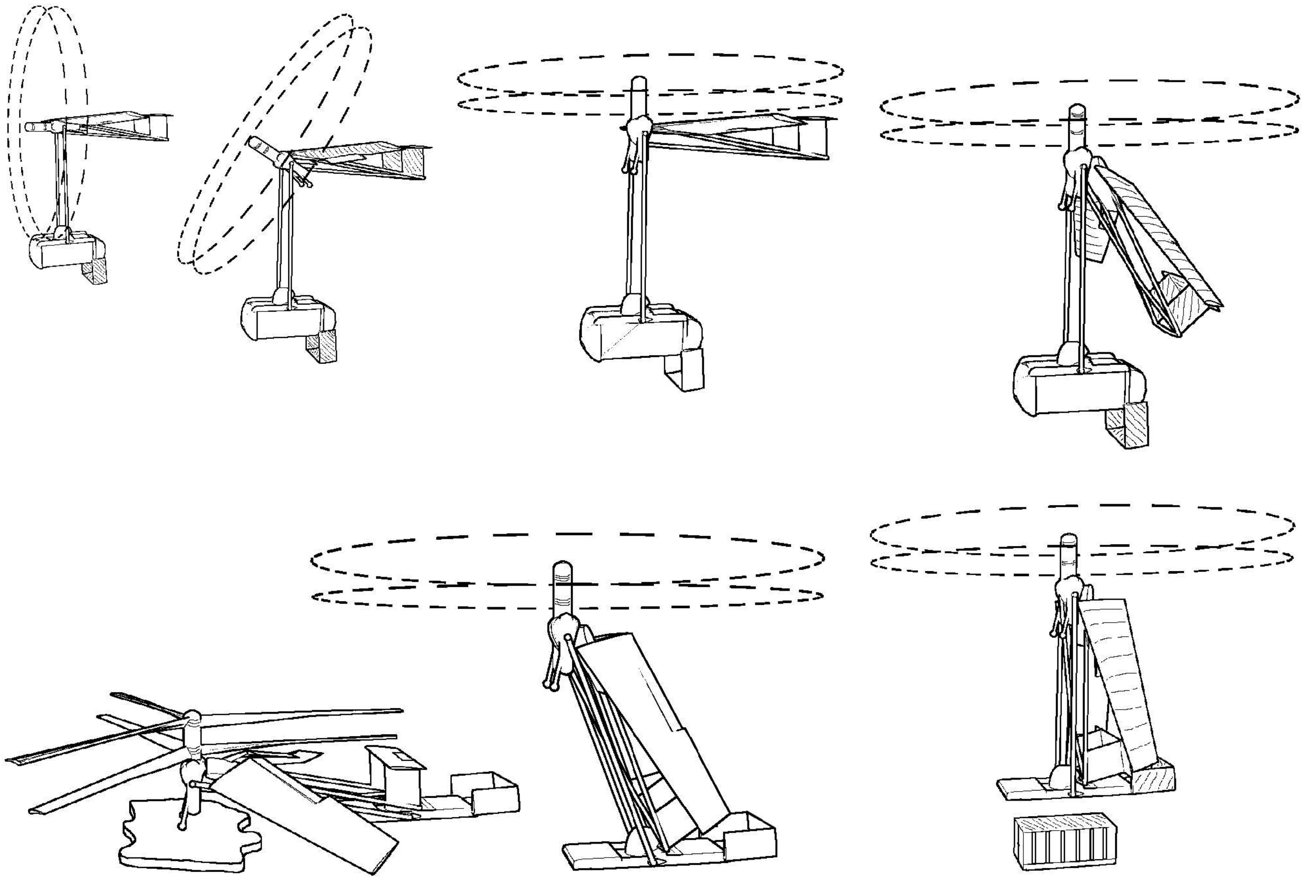

Figure 2: Conceptual sketch of the MTR transitioning from being at rest on the ground to hovering over a container, then morphing from helicopter mode to airplane mode.

Transition between hover and helicopter cruise mode was the next area examined. The coaxial rotor subsystem was presumed to have a self contained ability to transition between hover and helicopter cruise mode, without external stabilization or control input from a tail. This reasonable assumption is the subject of analysis as discussed in the Section on Work Underway, below. If the wing and tailboom could be designed to aerodynamically deploy during transition to helicopter cruise mode, mechanical actuation would be avoided and structural efficiency preserved. A mechanism to accomplish wing and tail aerodynamic deployment was developed. At the instant forward flight begins, the lower end of the suspension structure is locked to fix the payload pitch orientation, and the tailboom lower end is released from the payload allowing the freely pivoting tailboom to lift into a streamlined position as airspeed increases. It was discovered that by having freely pivoting wing panels with a kinematic arrangement similar to the wing fold of the Grumman TBF-1 Avenger, the wing panels would maintain a positive angle of attack while the wing and tailboom deploy together as a system. A kinematic/aerodynamic analysis and wind tunnel testing of this wing/tail subsystem deployment and retraction is the subject of yet another research study discussed in the Section on Work Underway, below.

Constant altitude conversion between helicopter mode and airplane mode was examined next. An initial approach was developed by mimicking conventional tiltrotors, where the wing offloads the rotor while a conversion actuator tilts the rotor into airplane mode. However, accommodation of the above constraints produced a configuration in which the gearbox rotates underneath the wing as the rotor masthead tilts forward. A conversion actuator is needed between the gearbox and the tailboom to cause a rotation of the gearbox about the upper end of the tailboom to a position underneath the fixed wing. Thus, the aircraft center of mass and the suspended load move back and underneath the wing to decrease airplane mode static margin as the wing loads up. A potential advantage of this configuration is that a failsafe-to-release conversion actuator would facilitate a failsafe-to-helicopter mode landing.

Generic Payload Unit

The payload unit had very few real physical constraints. First, a streamlined shape was needed to minimize flat plate drag area. Second, a vertical stabilizer was needed to provide yaw stability. A horizontal stabilizer was considered to be optional, because pitch stability is provided by the suspension structure, as described in the Section on Ideal Lift Unit, above. Third, active rudders at the vertical stabilizers integrated with a closed loop control system was contemplated to assure yaw alignment of the payload with the aircraft. And fourth, the payload needed to provide its own landing gear to support its weight and the impact of landing. Any generic payload meeting the above four constraints is suitable. This minimal set of constraints eliminates the conventional need for careful synergistic design between the aircraft and all conceivable future payloads. The modular design of the MTR easily accommodates new payload requirements after aircraft designs are frozen and in production.

Assessment of Scalable Value

In 2004, the Office of Naval Research funded the Conceptual Design Studies of a Mono Tiltrotor (MTR) Architecture. Quoting from the report's abstract...

> The present work reports on a conceptual design study that has been conducted to predict the sizes and weights of the MTR architecture and to objectively examine its potential performance. A detailed weight budget has been determined based on historical component data for helicopters and airplanes. A thorough component drag breakdown has allowed for good estimates of the overall lift-to-drag ratio of the MTR concept in both the helicopter mode and airplane cruise conditions. Various sizes of MTR have been examined, ranging from small machines with relatively light payloads of less than 5 tons to large heavy-lifters with payloads of 20 tons or more. A requirement was that the machine carry its payload over an unprecedented unrefueled distance of 1,000 nautical miles. The ability to morph the MTR so that its lift is created by a fixed wing when in cruising flight gives the machine a relatively high lift-to-drag ratio of about 14, good specific fuel consumption, and excellent net vehicle transportation efficiency in terms of payload carried per unit of fuel expended. It is shown that if technically realizable, the MTR architecture allows for a relatively compact and lightweight rotor design, with an accompanying lightweight airframe and relatively low fuel load compared to competing helicopter concepts. The results also show that structural weight efficiency is one key to the potential value of the MTR vehicle.

This lengthy and well documented report contains the following conclusions...

> The coaxial rotor and the relatively lightweight overall design of the MTR allow a much smaller vehicle with better weight efficiency than a conventional helicopter for any size of payload. This allows the MTR to carry less fuel and more useful payload over a longer flight range. Overall, the results suggest that if the MTR concept were in fact to be technically realized then it could be up to 50% smaller and up to 65% lighter than a conventional helicopter when carrying the same useful payload over the same distance.

...and...

> The proposed ability to morph the MTR architecture to fixed wing borne flight allows the vehicle to cruise at a substantially better lift-to-drag ratio and cruise speed than could be achieved with a conventional helicopter. This is the key to reducing overall vehicle weight, substantially improving its range, reducing fuel burn and improving overall operational economics.

Applications of the MTR Architecture

Subsequent to MTR aircraft architecture maturation, the U.S. Government has announced two sets of requirements that could be efficiently and effectively satisfied by an MTR based solution. The first set of requirements were issued in 2004 by the U.S. Army for a Joint Heavy Lift (JHL) aircraft. The second set of requirements were presented in 2005 by the Office of Naval Research for an Experimental Vertical Unmanned Utility Air Vehicle (XVU2AV). A brief summary of aircraft configurations suitable for these requirements is provided below, followed by an itemization of other potential applications.

A Joint Heavy Lift (JHL) Configuration

The conceptual design tools described above were applied to size an MTR configuration compliant with the JHL design requirements. The configuration is relatively compact, having an 79 foot diameter coaxial drive system with six blades per gimbaled hub. Power requirements can be exceeded by four off-the-shelf Rolls Royce AE1107C engines driving a single coaxial gearbox. In addition to the features described in the Section on Concept Overview above, a load carrying system was conceived to satisfy a variety of payloads.

MTR-JHL Payload Handling Concept

The MTR-JHL concept incorporates a technique for capturing, enveloping, streamlining, and optionally pressurizing a variety of payloads, including MILVANs, 40-foot ISO containers, Stryker, Essential Combat Configured (ECC) FCS, Full Combat Capable (FCC) FCS, and palletized loads. All payload capture and release operations are performed while the aircraft is in a hovering configuration. The technique has a load bearing component and an aerodynamic component.

Standard ISO containers provide the foundation of the load bearing component. The payload handling system has a spreader bar with ISO compatible bayonet twistlocks to retain and lift ISO containers, or any load having ISO standard load bearing corners. As shown in Figure 3, each bayonet twistlock has a weighted messenger line, similar to the Navy Recovery Assist, Secure and Transverse (RAST) system. The ISO container itself has an attached winch with hauldown cable.

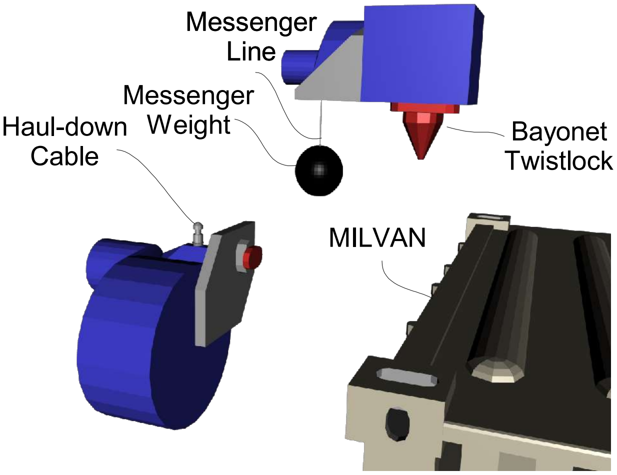

Figure 3: Bayonet twistlock with weighted messenger line, and associated winch.

The intended method of operation is to lower weighted messenger lines to an awaiting ground crew member. At the ground, each corner of the ISO container has a winch attached. The ground crew attaches the messenger line to the hauldown cable. As shown in Figure 4, the hauldown cable unspools while the messenger line retracts, until the hauldown cable becomes anchored aside the bayonet twistlock. The payload capture process is completed when the hauldown cable fully retracts, guiding the bayonet twistlock into the ISO corner top fitting. Eight bayonet twistlocks are provided, arranged for capturing either a MILVAN or a 40-foot ISO container. Capture may be performed either by lifting the container up or hauling the aircraft down.

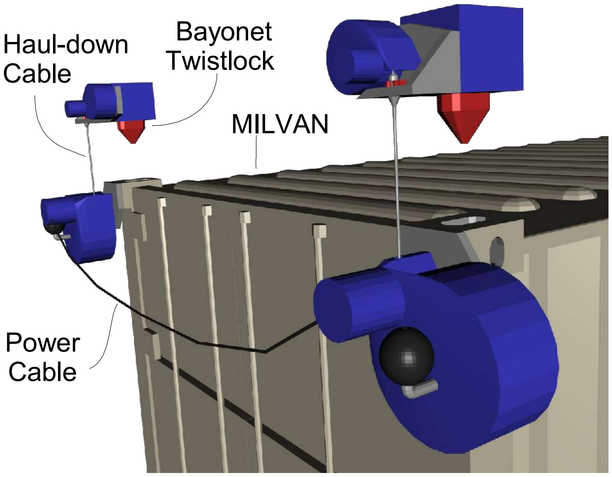

Figure 4: Hauldown cables retracting.

Operational value is developed through tailored payloads. In addition to capturing MILVANs and 40-foot ISO containers, this load bearing system has the capability to capture and transport a MILVAN attached to a M1077 Flatrack, or two interconnected MILVANs forming a 40-foot load. Furthermore, a Multi-function Payload Platform (MPP) concept supports a roll-on/roll-off Stryker, FCS, or a pair of armored HMMWVs, and has rails to accommodate 463L cargo pallets. As shown in Figure 5, each half of the MPP has two upper cross members for connecting to the payload unit spreader bar at the bayonet twistlocks. The two halves are joined together to support a Stryker or FCS.

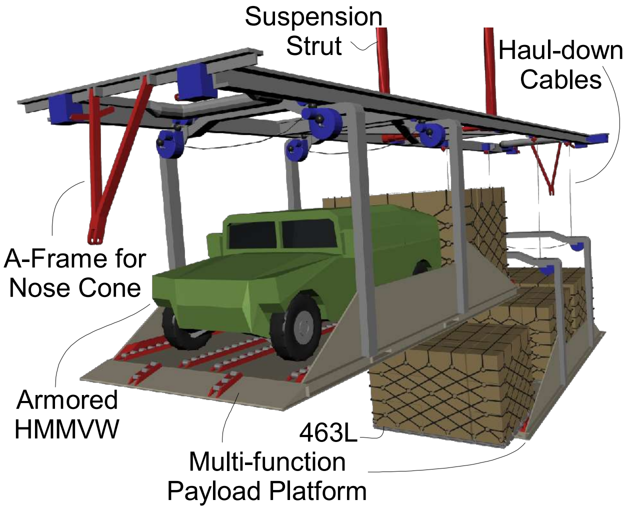

Figure 5: Multi-function Payload Platform (MPP) with HMMWV and four 463Ls.

The load bearing spreader bar is surrounded by and mounted to a collapsible aerodynamic fuselage. A bivalve nose-cone and a bivalve boat-tail provide the basis for the collapsible aerodynamic fuselage, with a pliable and airtight cloth completing the streamlined sides. Figure 6 shows two interconnected MILVANs mounted at the 40 foot bayonet twistlocks, with the cargo doors opened and the nose-cone in a fully collapsed

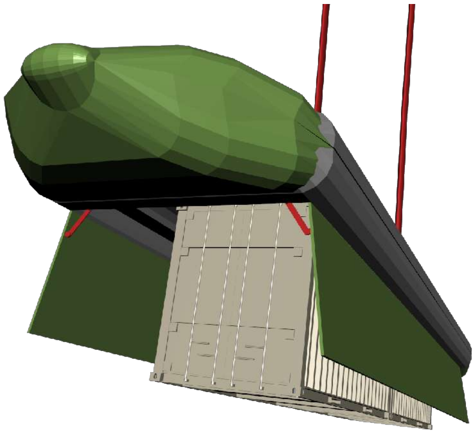

Figure 6: Two MILVANs mounted at the 40 foot bayonet twistlocks, with collapsed fuselage.

configuration. Figure 7 shows the nose-cone in a partially opened configuration, with the cloth sides of the fuselage beginning to unfold. The nose-cone has an upper and a lower half, hinged together near its leading edge. The trailing edges of the nose-cone are pinned to top and bottom structural frames. The boat-tail is of similar construction as the nose-cone and operates in a similar manner. A rigid upper deck and actuated cargo doors are mounted to the structural frames and complete the fuselage. An APU at the upper deck, fueled by a local feeder tank with replenishment provided through the suspension structure, delivers electric power and bleed air for pressurizing the fuselage. Positive pressure supports the cloth sides of the fuselage.

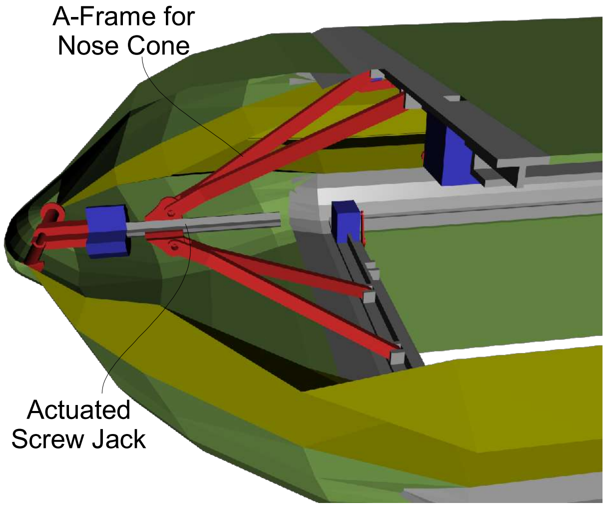

Figure 8: Sectional view of screw-jack mechanism for collapsing and expanding the nose-cone.

A sectional view of the nose-cone mechanism is shown in Figure 8. Two A-frames are pinned to the top and bottom structural frames, respectively. The upper A-frame is also visible in Figure 5. The peak of each A-frame is pinned to either side of a short tube. The tube is threaded onto an actuated screw-jack, and the screw-jack is pinned at the leading edge of the nose-cone. The nose-cone expands when the screw-jack pushes the tube aft, and collapses when the screw-jack pulls the tube forward. The tail-cone is of similar construction and operates synchronously with the nose-cone.

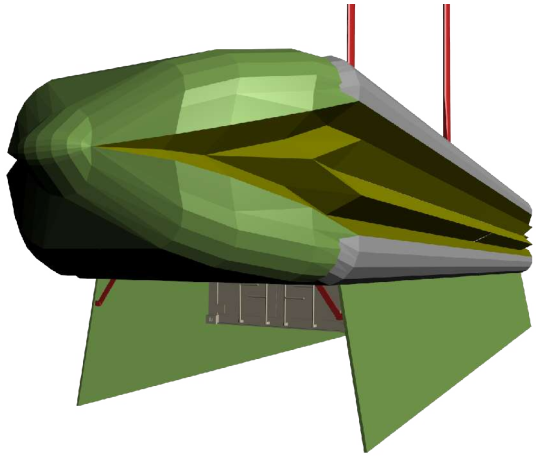

Figure 7: Nose-cone partially opened, with cloth sides of fuselage beginning to unfold.

Compact, Unloaded Configurations of the MTR-JHL Concept

While aircraft are productive only when loaded and in operation, inevitable circumstances will arise when the vehicle is unproductive. The MTR-JHL concept specifically addresses the need for minimizing the burden of these unproductive circumstances. The two most burdensome circumstances are dead heading back to a supply point after releasing a load, and stowing the aircraft on a ship when not in operation.

A dead heading configuration can significantly reduce cruise drag, minimizing dead head fuel burn while increasing cruise speed. The dead head configuration as illustrated in Figure 9 is achieved by collapsing the fuselage and sealing the cargo doors into a low profile, streamlined configuration. In this configuration, the MTR operates efficiently at a much higher cruise speed while returning to a distribution point. Throughput is increased while the fuel burden is reduced.

The MTR-JHL concept has two features for reducing stowed footprint while simplifying ground operations. The first feature is a telescoping suspension structure with axillary tailboom latch at the boat-tail. With this feature, the drive system lands atop the payload deck, as shown in Figure 10, reducing the length of the shipboard capable stowed footprint. The payload top would have a heat resistant landing deck, protecting the runway from direct hot engine exhaust. The second feature is retractable landing gear attached to the payload spreader bar. Ship board compatibility would require that each set of six rotor blades be folded back, and each wing panel be folded up.

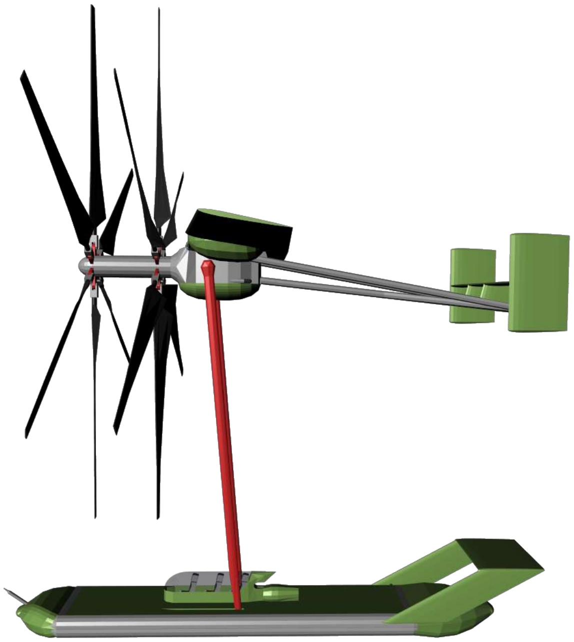

Figure 9: MTR in low drag Dead Head configuration.

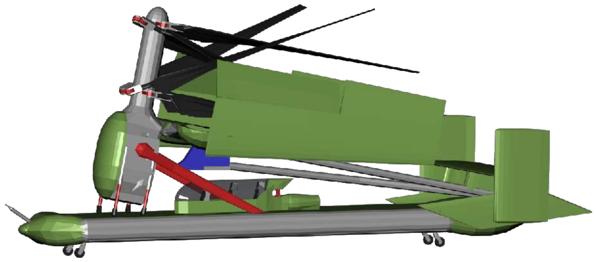

Figure 10: MTR folded for compact stowage and shipboard compatibility.

Summary of MTR-JHL Concept Technical Data

Dimensioned engineering drawings of the MTR-JHL concept operating in airplane cruise are provided in Figure 11, and in a folded and stowed configuration are provided in Figure 12.

Vertical Unmanned Utility (XVU2AV) Concept

The notional requirements for the Navy XVU2AV include the ability to stow and transport the aircraft inside an 8ft x 8ft x 20ft ISO container, vertically lift a 3000 pound load, and transport the load at a speed of 230kts over a range of 175 nm to 400 nm. A technically successful subscale implementation of the MTR-JHL concept described and illustrated above would meet the stowage requirements and exceed the performance

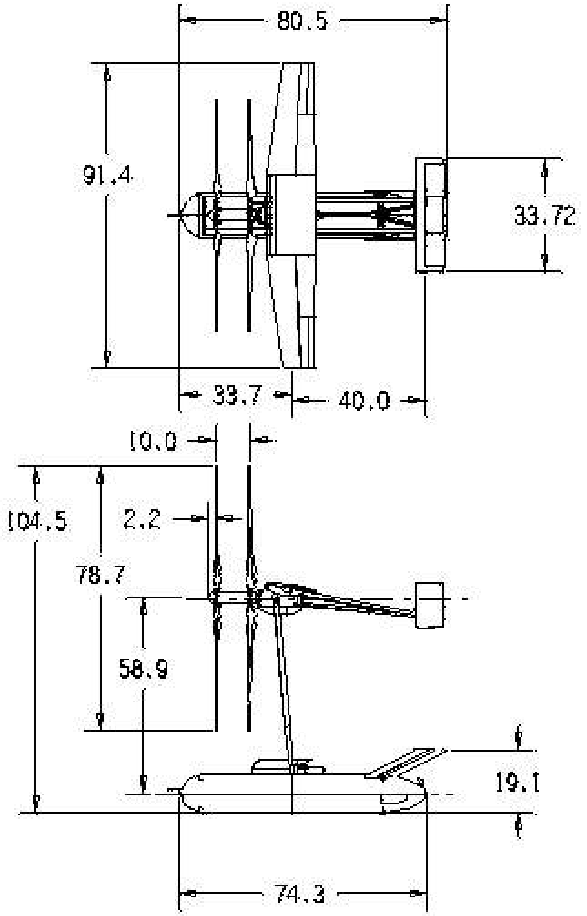

Figure 11: Dimensioned engineering drawing of MTR-JHL with enveloped load in cruise mode.

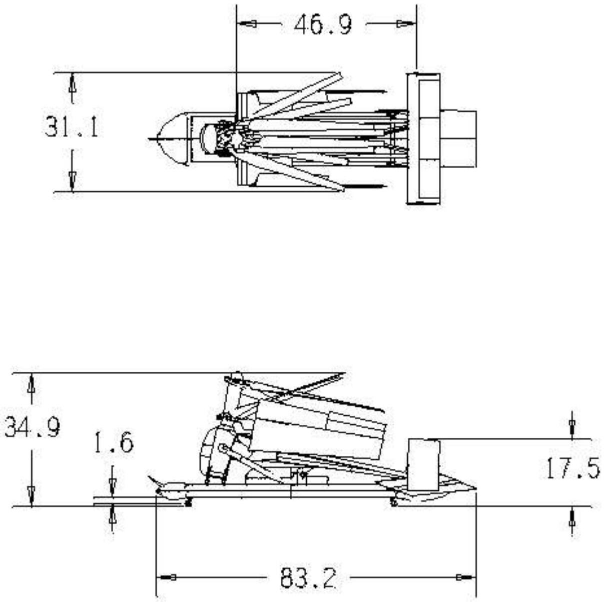

Figure 12: Dimensioned engineering drawing of MTR-JHL in stowed configuration.

requirements. A preliminary design project to provide technical validation at this scale is currently underway, as described in the Section on Work Underway, below. This preliminary design includes a pair of Rolls Royce T800 engines providing more than sufficient power in a suitably compact configuration. The target payload container is the 42in x 44in x 54in Joint Modular Intermodal Container (JMIC).

Other Applications

After achieving prerequisite military operational capability, the MTR aircraft architecture may find a variety of suitable commercial applications. A likely initial scenario is that smaller implementations of the MTR aircraft architecture would find a variety of military and commercial applications as a UAV logistics delivery platform. While direct commercial application of a heavy lift MTR to airborne ISO container transport might initially seem attractive, the economics of speed in container shipping may not support a profitable business model. A heavy lift MTR with a redesigned payload system may have value as an inter-city transport. Passengers might board a disconnected fuselage, awaiting an available MTR for transport. The MTR would have high utilization, never waiting on the ground for passengers to embark or disembark. Maintenance and refueling could be performed at regional depots, away from passenger stations. Integration of mid-sized MTR lift systems with automobile like vehicles is beyond the foreseeable economic horizon.

Work Underway

The MTR R&D Team is performing a 12-month task order for the Army Aviation Applied Technology Directorate (AATD) to advance the understanding of the MTR and its ability to meet notional heavy lift requirements. Specific attention is being paid to analytical modeling of key subsystems and their ability to perform as intended. Systematically addressing specific subsystem design and analysis and their impact on total system weight and drag will assist in reducing the overall technology risk associated with this platform. Work underway includes a preliminary design and engineering analysis of a Scaled Demonstrator (SD) vehicle, and performance analysis and testing of a much smaller Parametric Research Model (PRM). Knowledge gained from these activities is being applied to a conceptual design feasibility study against notional heavy lift requirements. The work is scheduled to be completed in the Summer of 2006.

Scaled Demonstrator (SD) Preliminary Design

The MTR-SD is sized to lift a 4000 pound load, and transport this load without refueling at a cruise speed of 200kts over a distance of 700nm. Engineering problems solved at this scale will significantly reduce technical risk of larger configurations. Furthermore, a vehicle of this scale is suitable for wind tunnel testing. Work performed on the SD is applicable and directly transferable to the XVU2AV concept described above. An aerodynamic analysis of the coaxial proprotor was performed by the University of Maryland (UMd) Alfred Gessow Rotorcraft Center to predict hovering figure of merit and axial propulsive efficiency, with results to be presented at the AHS Forum 62. The analytical methods included Blade Element Momentum Theory (BEMT) and Free-Vortex Wake Method (FVM). Aeroelastic and comprehensive analyses of the major subsystems and the complete integrated system are being performed by the Army Research Lab (ARL) - Vehicle Technology Directorate. These analyses are being performed in CAMRAD II and DYMORE. CAMRAD II is the Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics. DYMORE is a finite element based tool for the analysis of nonlinear elastic multibody systems. Preliminary design of the MTR-SD rotor blades, hub, controls, and tilt actuator are being performed by Eagle Aviation Technologies Incorporated, with design iterations incorporating the analytical results produced by UMd and ARL. Design decisions made to-date include rigid hubs, four rotor blades per hub, gearbox conceptual layout, and selection of a pair of Rolls Royce T800 engines. An illustration of the MTR-SD in a folded configuration and stowed in a 20ft ISO container is provided in Figure 13.

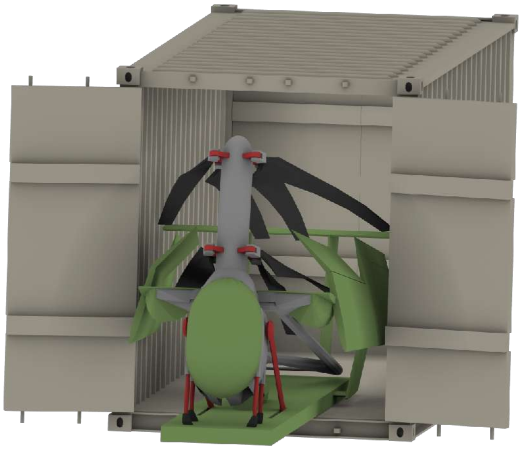

Figure 13: MTR Scaled Demonstrator in folded configuration and stowed in a 20ft ISO container.

Parametric Research Model (PRM)

The Parametric Research Model (PRM) is a geometric sub-scale representation of the MTR-SD preliminary design. The purpose of this model is to quantify the deployability of the MTR wing panels with aerodynamic forces and to measure the corresponding lift and drag. A key parameter for aerodynamic wing deployment is the pivot axis offset angle of each wing panel relative to the center wing box. As part of the PRM design process, a kinematic/aerodynamic computational model of wing and tail deployment was developed by UMd. Predictions of the aerodynamic angles of attack along the wing allow for an estimate of the aerodynamic forces and moments acting on the wing during its folding sequence. Aerodynamic loads on all wing and tail components were incorporated, and balanced against all wing and tail inertial forces. The computational analysis was performed first as a static, force balanced analysis for a range of wind speeds, and then as a dynamic, time-marching analysis. This computational model will be validated against wind tunnel empirical data to be collected during unpowered experiments in the Glenn L. Martin 7.5'x11' Wind Tunnel in Spring 2006. The PRM has several candidate wing panel hinges which are modular and easily replaced during the testing period. A rendering of the PRM is provided in Figure 14.

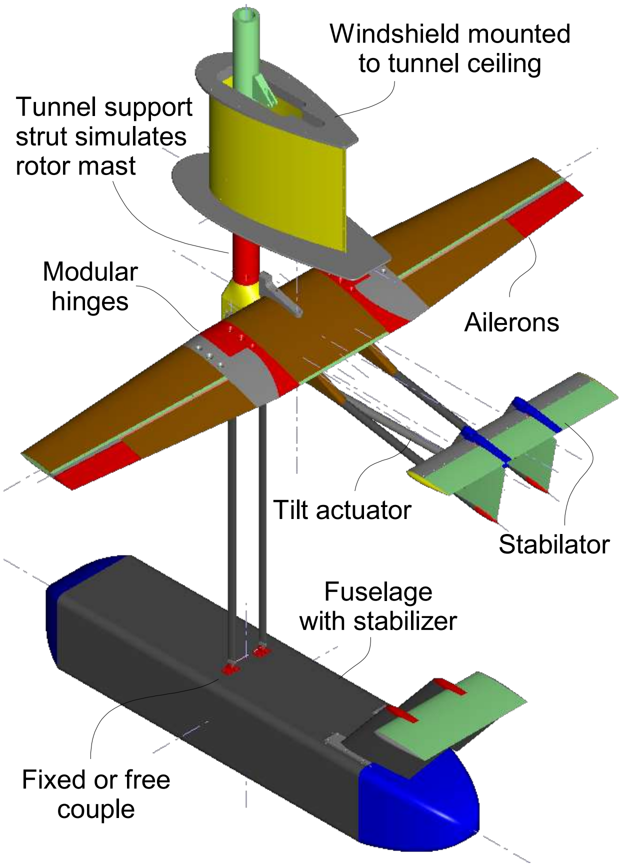

Figure 14: Rendering of the MTR Parametric Research Model with wing and tail deployed.

Heavy Lift (HL) Preliminary Analysis

Knowledge developed during the design, analysis, and test of the Scaled Demonstrator (SD) and Parametric Research Model (PRM) is being applied to refining an MTR Heavy Lift (HL) conceptual design. The rotor aerodynamic models used to optimize the SD rotor design for both hover and propulsive efficiency are being applied to designing HL rotor blades. The comprehensive and aeroelastic models developed in support of the SD preliminary design will be adjusted to reflect HL inertial properties, material properties, dimensional properties, etc. and then re-analyzed to identify similarities and differences between the SD preliminary design and a notional HL concept. One likely difference identified through early analytical results is that while SD rotor trim in all flight modes may be achieved with a rigid hub, the HL configuration will likely require a gimbaled hub, and perhaps would benefit from having on-blade control. The validated PRM kinematic/aerodynamic models will be applied to predicting HL wing and tail deployment methods. When complete, the HL analysis will provide detailed information on MTR scalability. The HL preliminary analysis is scheduled to be completed in Summer 2006.

Risk Management

Risk is being managed through the early identification of potential fundamental issues, and developing methods to isolate and explore each issue while expending minimal resources. A prototypical example of this method is the initial free-flight test of the pitch axis suspended load described in the Introduction, above. While the thought of increased stability seemed reasonable, the fact was known through low-cost demonstration. Next, a series of known issues typically faced by VTOL concepts were identified and addressed through the steps described in the Concept Overview, above. Once the MTR architecture was mature, its potential economic and operational value could be readily assessed using industry standard conceptual design tools. Having passed this evaluation, the next goal was identification of a representative scale providing both potential military capability and useful engineering knowledge. Both a Heavy Lift and a Scaled Demonstrator configuration have been identified. Regardless of eventual real application, the Scaled Demonstrator would need to be completed to justify Heavy Lift development resource allocation. Meanwhile, fundamental research is cost effectively performed on the Parametric Research Model. The initial low-cost PRM test will demonstrate wing and tail deployment in a freestream, and the empirical data gathered will be applied to validating the analytical tools. With a successful outcome, a next step will be to incorporate a rotor wake into the analytical model, and add an upstream coaxial rotor to the physical model. PRM results will be incorporated into the Scaled

Demonstrator preliminary design and analysis activity. The subsequent research path will likely focus on SD physical modeling and testing, since the Reynold's Number, inertial properties, and material properties are representative of a militarily useful scale vehicle. Before committing resources to this larger physical demonstration, much of the risk will have been addressed and understood through PRM testing and SD preliminary and detailed design.

Conclusions

The Mono Tiltrotor (MTR) has been proposed, as an innovative heavy-lift rotorcraft architecture. The MTR architecture integrates a coaxial rotor, a folding lifting wing system and an efficient cargo handling system. This paper has reported on the innovative steps taken to mature the MTR aircraft architecture, a summary of MTR aircraft concepts suitable for emerging military needs, and progress in developing MTR knowledge.

The following specific conclusions have been drawn from this work:

1. Maturation of the MTR aircraft architecture has occurred in a collaborative, unlimited data rights environment, with results published and communicated to the rotorcraft community in Government reports, conference papers, and over the Internet.
2. Aircraft based on the MTR architecture if technically realized have the potential to deliver unprecedented capabilities in range, speed, and compact stowage. Furthermore, the modular architecture of the MTR eliminates the conventional need for careful synergistic design between an aircraft and all conceivable future payloads.
3. A morphing fuselage concept for capturing, enveloping, streamlining, and optionally pressurizing containerized loads has been defined. This fuselage concept is applicable to ISO intermodal containers and the emerging JMIC container, and when unloaded has a minimal profile for efficient deadheading and compact stowage.
4. A methodical approach to developing practical MTR knowledge is underway, incorporating preliminary design, preliminary analysis, and wind tunnel testing activities.
5. Program risk is being managed by early identification of potential fundamental issues, and developing methods to isolate and explore each issue while expending minimal resources.

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