Proceedings of the 2020 Annual General Donald R. Keith Memorial Capstone Conference
West Point, New York, USA
April 30, 2020
A Regional Conference of the Society for Industrial and Systems Engineering

Modernizing the AH-64 Tail Rotor

Kelly Azinge, Cole Christiansen, Charles Moseley, Jay Peterson, Roderick Stoddard, and Michael Parrish

Department of Systems Engineering
United States Military Academy, West Point, NY

Corresponding Author: kelly.azinge@westpoint.edu

Author Note: The authors of this paper participated in a year-long senior project in the Department of Systems Engineering at the United States Military Academy (USMA). Pending graduation in May 2020, the authors will commission as Second Lieutenants in the United States Army as Aviation, Chemical, Engineer, and Field Artillery officers. This project was conducted under the advisement of Mr. Michael Parrish, who currently serves as an instructor at USMA. We would like to thank Mr. Matthew Sipe at PEO Aviation for his assistance with the project year-round in addition to Mr. Brad Paden at LaunchPoint Technologies for providing us with the e-TR system and report.

Abstract: The United States Army is preparing to face near-peer threats with similar or better battlefield technology. This threat has driven a movement to modernize the force's current battlefield systems. Future vertical lift ranks third on the Army's list of modernization priorities. While the Army is preparing to acquire entirely new aircraft, the AH-64 Apache will remain an integral part of the fleet for the next 30 years. To maintain its relevance and improve its capabilities, the Army is evaluating the potential development of an electric tail rotor system to replace the current mechanically driven system. The purpose of this project is to assess the feasibility of converting to an electric system. The System Decision Process was utilized to identify and weigh potential solutions. The model assigned the greatest value to a magnetically driven, electric system with a Fenestron shroud. This signifies the movement away from the traditional, exposed tail rotor blades.
Keywords: AH-64 Apache, Army Modernization, Electric-Tail Rotor, Magnetic Motor, FARA

1. System Need

1.1 The AH-64 Apache

The AH-64 Apache helicopter conducts a versatile mission for the United States Army. Specifically, the AH-64 "Conducts armed reconnaissance, close combat, mobile strike, and vertical maneuver missions when required, in day, night, obscured battlefield, and adverse weather conditions." (AH-64E Apache Attack Helicopter) The Apache has served in this role for decades. While the Army has created a program to acquire a Future Attack Reconnaissance Aircraft (FARA), it is expected that the current AH-64 will remain in the Army's fleet until at least 2050 (Mr. Sipe, personal communication, September 5, 2019). In order to maximize the operational capability of the AH-64 for the next 30 years, the Army Project Executive Office Aviation – the project's key stakeholder, seeks to assess a system that will convert the mechanically driven tail rotor to an electric tail rotor.

1.2 Traditional Tail Rotor System

The primary function of the tail rotor is to provide anti-torque to prevent the helicopter from entering a spin due to the torque produced by the main rotor (Cantrell). The AH-64 Apache utilizes a traditional, mechanically driven, four-bladed tail rotor. In the traditional system (Figure 1), the main transmission powers the tail rotor drive shaft. The tail rotor drive shaft powers the intermediate gear box which powers the tail pylon drive shaft. The tail pylon drive shaft then powers the tail gear box, which spins the tail rotor blades. The power for both the main rotor and the tail rotor comes from two turboshaft engines (Woodford, 2020).

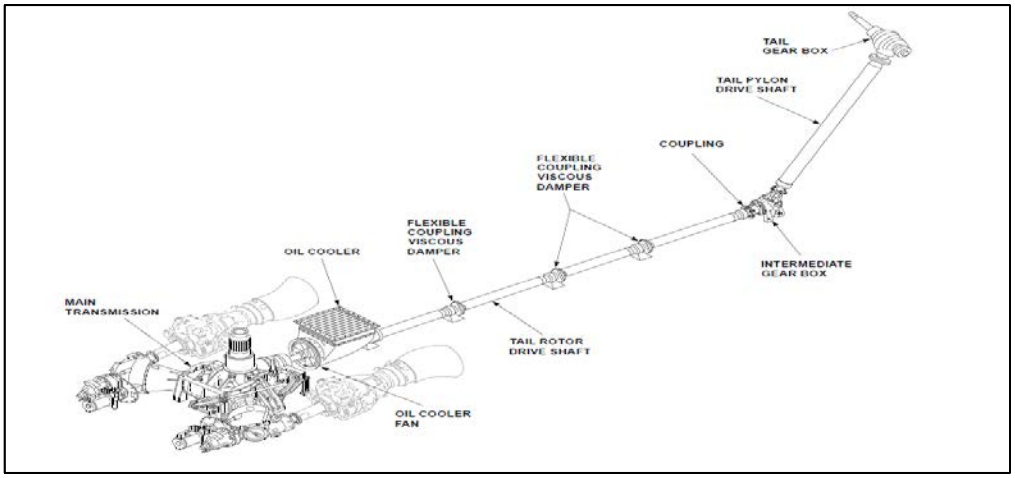


Figure 1. Traditional Tail Rotor System of a UH-60

1.3 Disadvantages of Mechanically Driven Tail Rotor Systems

Mechanically driven systems present both safety and performance concerns. Largely, these issues stem from the complexity of the system. In a mechanically driven system, a gearbox, or drive shaft failure will most likely result in total loss of rotor functionality and loss of control of the aircraft. This type of system failure contributes to an estimated 15% of the tail rotor accident rate (Ricci, Helicopter Electric Tail Rotor Drive 37). Crashes due to tail rotor failure, commonly known as loss of tail rotor effectiveness, account for 21% of all helicopter crashes ("NOTAR Technology"). Further, the exposed tail rotor blades are subject to external aggressors. Another common cause of helicopter accidents is the tail rotor hitting an obstacle, losing anti-torque, and crashing after entering an uncontrollable rotation (Cantrell). While this traditional system has served the AH-64 for many years, it is subject to modernization that will lead to increased safety and performance.

2. Methodology

2.1 The Systems Decision Process

The Systems Decision Process (SDP) was utilized throughout this project. The SDP is an iterative process consisting of four main steps: Problem Definition, Solution Design, Decision Making, and Solution Implementation. Each of the four main steps consists of multiple sub-steps that can be conducted as many times as necessary to achieve the desired output. This project culminates in the Decision Making step of the SDP with the creation of a dynamic quantitative value model used to score and analyze multiple solutions.

3. Problem Definition

3.1 Functional Hierarchy

A functional hierarchy (Figure 2) was created to identify the system functions and sub functions needed to meet performance objectives. The fundamental objective is to modernize the AH-64 tail rotor system through conversion to an electric system. This objective is broken into three main functions: (1.0) Provide Anti-Torque, (2.0) Provide Electric Power, and (3.0) Serve the Needs of the Unit. These main functions are further broken down into several sub functions.

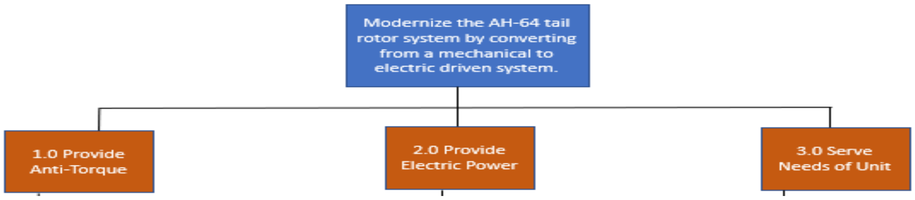
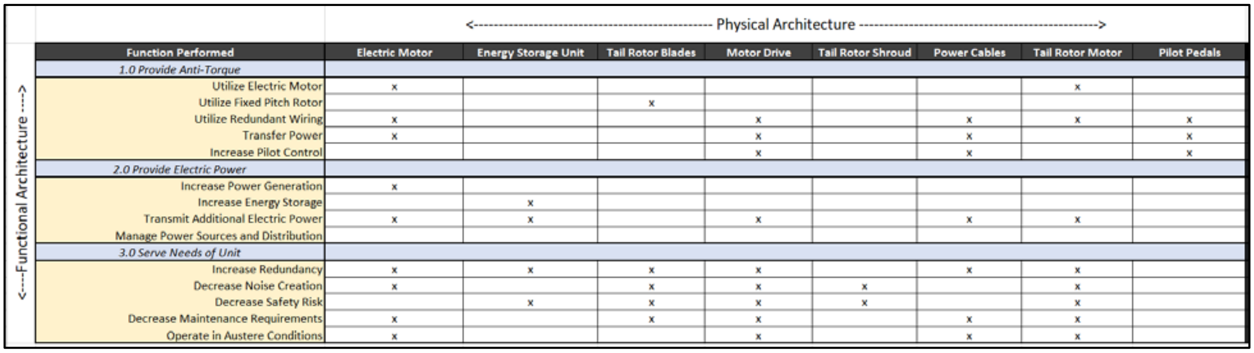


Figure 2. Top-Level Functions of Functional Hierarchy

3.2 Functional/Physical Matrix

A deeper functional analysis was conducted with the creation of a Functional/Physical matrix (Figure 3) to allocate each sub function to a specific solution part. This requirements flow down was a key deliverable of the project and was accepted by the client.


<-- Physical Architecture -->

<----Functional Architecture ---->

Function Performed	Electric Motor	Energy Storage Unit	Tail Rotor Blades	Motor Drive	Tail Rotor Shroud	Power Cables	Tail Rotor Motor	Pilot Pedals
1.0 Provide Anti-Torque								
Utilize Electric Motor	x						x	
Utilize Fixed Pitch Rotor			x					
Utilize Redundant Wiring	x			x		x	x	x
Transfer Power	x			x		x		x
Increase Pilot Control				x		x		x
2.0 Provide Electric Power								
Increase Power Generation	x							
Increase Energy Storage		x						
Transmit Additional Electric Power	x	x		x		x	x	
Manage Power Sources and Distribution								
3.0 Serve Needs of Unit								
Increase Redundancy	x	x	x	x		x	x	
Decrease Noise Creation	x		x	x	x		x	
Decrease Safety Risk		x	x	x	x		x	
Decrease Maintenance Requirements	x		x	x		x	x	
Operate in Austere Conditions	x			x		x	x	

Figure 3. Requirements Matrix

3.3 Qualitative Value Model

A qualitative value model (Figure 4) was constructed utilizing information gathered through research, stakeholder analysis, and functional analysis. The 'Fundamental Objective' line represents the overarching problem to be solved. The 'Functions' line represents the main functions that were developed with the creation of the functional hierarchy discussed earlier. The 'Objectives' line identifies the overall requirements that the new system will meet. Each objective is further broken down to one, or multiple value measures. These value measures are used to conduct analysis on each alternative and its ability to meet each objective.

4. Alternative Generation

4.1 Electric Tail Rotor

Research was conducted into current and pending technologies available to the aviation community. Various electric power sources such as battery and magnetic were evaluated. Based upon the stakeholder approved

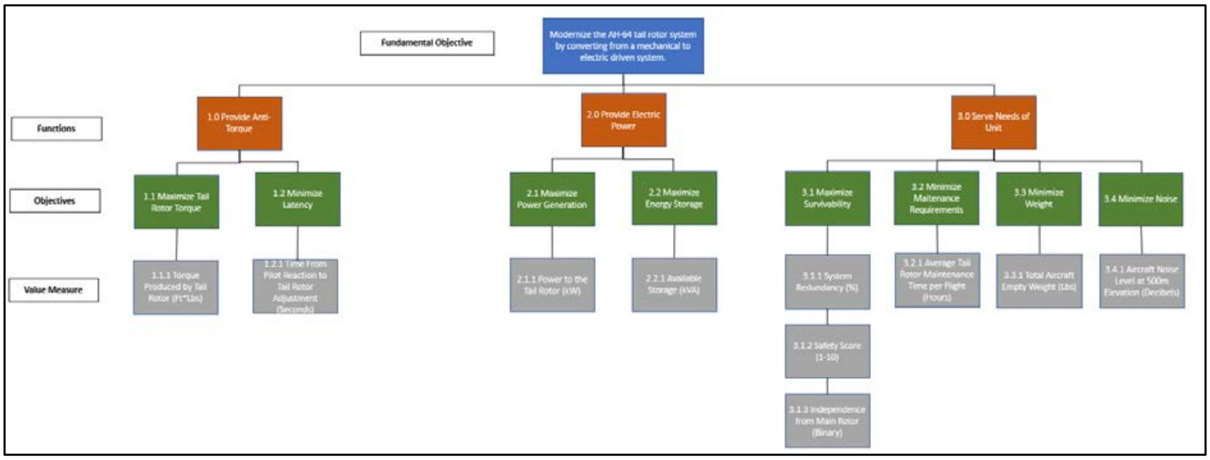


Figure 4. Qualitative Value Model

requirements described above, only one power source, the magnetic motor, was determined feasible. This alternative system (Figure 5) is an electric tail rotor system driven by a magnetic motor that was previously designed and tested on the Bell 206 helicopter by LaunchPoint Technologies who supported this project. This system proposes several advantages that, with proper conversion to the AH-64, could provide the improved performance and safety specifications requested by our client.

This system utilizes an electric tail rotor drive powered by the Halbach array ironless electric machine (Ricci, Helicopter Electric Tail Rotor Drive 5). This system operates independently from the main rotor and thus provides several advantages. Forward flight can be made more efficient by slowing or turning off the tail rotor and using the tail fin to create anti-torque. System redundancy is increased by the creation of a two-stack electrical motor. Thus, if one stack fails, there is enough power generated by the second stack to continue to hover and maneuver in moderate conditions. Further, each stack will be wound with two independent 3-phase windings (Ricci, Helicopter Electric Tail Rotor Drive 14). Through elimination of the single, mechanical drive, this system is more resistant to ballistics. The system within the tail boom of the helicopter consists of multiple independent power transmission paths that can be located with some distance between them, making it almost impossible to lose power due to the destruction of the cables. This system reduces the amount of single point failures through the removal of gears and tail shaft bearings. Further, as the system operates separately from the main rotor, it will not always be rotating when the main rotor is spinning. This increases safety on the ground as the tail rotor will be stationary until just before takeoff. Finally, the independence of the main rotor will also allow for tail rotor speed to be varied to enable increased safety in hazardous flight conditions (Ricci, Helicopter Electric Tail Rotor Drive 29-30).

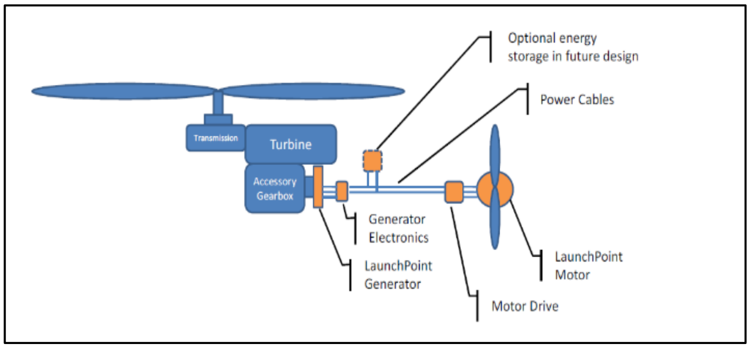


Figure 5. LaunchPoint Technologies' e-TR

4.2 Electric Tail Rotor with Fenestron Shroud

To further optimize the potential solution, a second alternative utilizing the LaunchPoint system with a fenestron shroud to protect the tail rotor blades was evaluated. The addition of the fenestron shroud provides several operational advantages in addition to the advantages listed with the above system. The fenestron design consists of several blades mounted within a protective shroud. This system requires less power, offers increased redundancy, reduces noise production, and increases safety from external aggressors (Vuillet &Morelli, 1986). The main disadvantage that accompanies this system is the additional weight from the protective shroud.

5. Decision Making

5.1 Quantitative Value Model

A quantitative value model was created utilizing the value measures developed in the Problem Definition phase. This is a fluid model that required many assumptions. Specifically, PEO Aviation emphasized that the stakeholder weights assigned to each value measure are subject to change throughout the acquisitions process (Figure 6). Further, precise data was not obtainable due to the testing needs for several of the value measures. However, assumptions were made based on research that allowed for an initial value scoring of each alternative.

	WEIGHTS									
	TR Torque	Latency	Redundancy	Safety Score	Helicopter Empty Weight	Tailrotor Independence	Noise	Maintenance Requirements	Tail Rotor Power	Energy Storage
Swing WT	70	60	90	90	40	40	30	80	80	80
Measure WT	0.11	0.09	0.14	0.14	0.06	0.06	0.05	0.12	0.12	0.12

Figure 6. Stakeholder Value Weights

5.2 Model Results

Figure 7 depicts a comparative analysis of each alternative. Based on the initial assumptions and stakeholder weights, the Electric Tail Rotor w/ Fenestron outscored the Electric Tail Rotor by an extremely small margin. Each system greatly outperforms the current AH-64 system. The stacked bar chart depicts where value was created with each system. The model suggests that the movement to a new tail rotor system will generate a significant amount of value relative to the current system. The model further indicates and supports the movement towards a shrouded tail rotor. This is a movement that is seen in both modern commercial and military rotorcraft, such as; Bell's EDAT system, and the FARA prototype generated by Bell.

There is a significant difference between the highest scoring solution and the ideal system. Largely, this difference is generated from a single value measure: energy storage. The ideal solution possesses an energy storage system that allows for power to be transferred to the tail rotor in the event of a motor failure. This is not included on the evaluated systems due to the lack of developed technology in this sector.

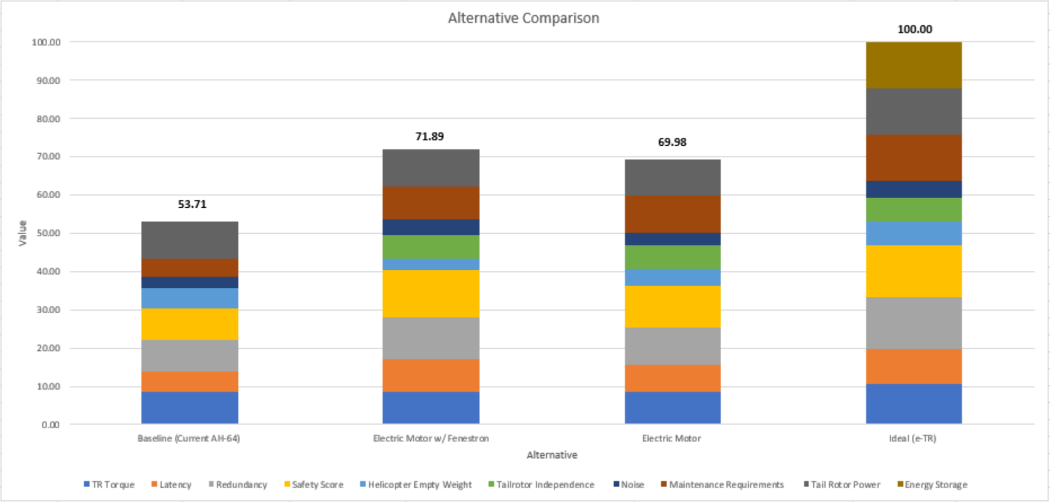


Figure 7. Value Stacked Bar Chart

5.3 Sensitivity Analysis

Sensitivity analysis was conducted to measure the impact of changing stakeholder weights on the total value of the system. This analysis was conducted on the value measures with the greatest stakeholder weights; redundancy (Figure 8) and safety (Figure 9). The results of the sensitivity analysis indicated that the model results (Overall Value) is not sensitive to the weight assigned to either value measure. While there is intersection, it does not happen within +/- 10% of the original swing weight value and thus cannot be considered sensitive. This is likely due to the assumptions that were made to construct the model. More specific measurements may result in increased variations across the value measures and thus result in greater sensitivity.

6. Conclusion

6.1 Future Work

This project provides an initial baseline model that can be utilized to measure the value of various tail rotor systems. The most significant drawback of the model are the multiple assumptions that were made. These assumptions can be eliminated through the gathering of precise values. This requires the testing of the tail rotor systems and development of a more precise value matrix by the user of the model. While the model is generally accurate due to the assumptions, a much more accurate model can be developed by testing each system. Further, a cost analysis can be conducted once the costs of each system are determined, which was beyond the scope of this project.

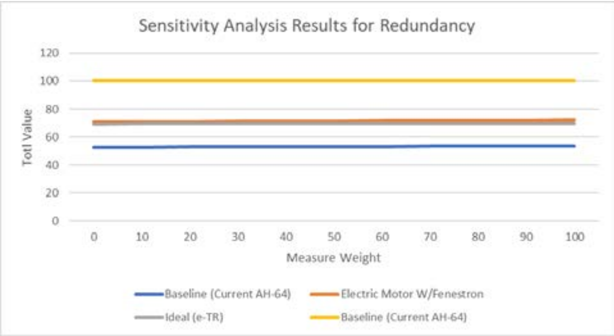


Figure 8. Redundancy Sensitivity Analysis

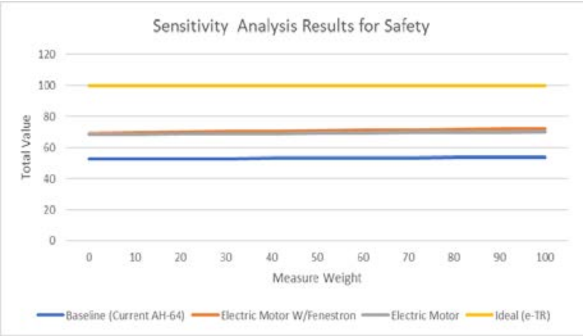


Figure 9. Safety Sensitivity Analysis

6.2 Impact

This project identifies the value that can be created through the conversion to an electric tail rotor system. It further identifies the necessary improvements that stand to be made in the electric tail rotor industry. The greatest tradeoffs when converting to the electric motor was the additional weight from the motors which needs to be further evaluated to determine its impact on the aircraft's center of gravity and overall weight and balance calculations.

7. References

AH-64E Apache Attack Helicopter. *Army.mil*, U.S. Army, Retrieved from: www.army.mil/article/137579/ah_64e_apache_attack_helicopter

Cantrell, P. (n.d.). Helicopter Tail Rotors. Retrieved November 14, 2019, from: http://www.copters.com/mech/tail_rotors.html

NOTAR Technology. MD Helicopters, *MD Helicopters*, Retrieved from: https://www.mdhelicopters.com/notar.html.

Figure 1. Pages from TM 1-1520-280-23&P, 28 February 2019, Distribution D, Revision 1.

Ricci, M., & Sugar, J. (2013). LaunchPoint Technologies, Goleta, CA. *Helicopter Electric Tail Rotor Drive*. Final Report 11 Nov 13. Arlington, VA Office of Naval Research (US). Contract Number: N00014-13-P-1095. Available for U.S Government Agencies Only.

Sipe, M. (2019). *Initial Client Meeting.* [Interview with Capstone Team]. PEO Aviation.

Vuillet, A., & Morelli, F. (1986). *New Aerodynamic Design of the Fenestron for Improved Performance*. Twelfth European Rotorcraft Forum.

Woodford, C. How Does a Helicopter Work?: Who Invented Helicopters? Helicopters. *Explain That Stuff*, Retrieved January 7, 2020 from: https://www.explainthatstuff.com/helicopter.html#tailrotor.