Rewiring the Human Brain: Mastering Helicopter Emergencies through System Dynamics

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Abstract

The tail rotor on conventional helicopters counterbalances the power of the engine and if it fails, the aircraft can spin uncontrollably and crash. Pilots are given training on how to safely recover and land their helicopters during a tail rotor emergency and yet when it occurs, many pilots fail to act effectively, or worse, do the *opposite* of what they have been trained to do. This paper presents a position where the problem is not the pilot's knowledge causing them to crash, but how they are taught. To present this case, a System Dynamics model, developed in 2018, is used to describe helicopter flight and how pilots are part of the system-of-systems as "human-in-the-loop". The training process required for pilots to fly helicopters is also described along with its limitations, especially in preparing students for emergencies. A series of additional System Dynamics models, correlated to real-world data, are presented to show the effects of a tail rotor failure on the system, the recommended recovery method, and the pilot decision flow to make the recovery. Finally, this paper describes how System Dynamics can be used to improve pilot efficacy, especially in emergencies, and concludes with a case study, and personal story from the author, on the real-life use of System Dynamics to save lives in a helicopter crash.

An Example of The Problem

On May 19, 2012, in Pittsfield, Pennsylvania, a student pilot, flying a Hughes TH-55 helicopter, was completing a flight and approaching the airport. The helicopter started spinning to the right uncontrollably despite all attempts by the pilot to arrest it. According to the official accident investigation report, *"The pilot stated that he then increased collective pitch and the corresponding increase in engine power aggravated the spin."* The helicopter crashed hard, rolled over on its side, and was substantially damaged. [1]

The uncontrollable spinning of the TH-55 helicopter was the result of the tail rotor failing to produce the thrust required to counteract the engine. Before being allowed to fly the helicopter solo, the student pilot would have first completed ground school, or classroom instruction, where he would have received lectures, studied, and pass written tests on the operations and emergency procedures of the TH-55, including a loss of tail rotor thrust. Furthermore, the TH-55 Operator's Manual states in Section 9-20, *"If total loss of tail rotor thrust is experienced, close the throttle immediately and accomplish an autorotation landing [decrease collective]."* [2] Unfortunately, per the accident report cited above, the pilot's actions in the cockpit were exactly the *opposite* of the Operator's Manual instructions and what he learned in ground school resulting in a crash of the helicopter. Tail rotor failures are chaotic and disorienting, and even though pilots have the "book knowledge" to survive, this mistake still commonly occurs because it is simply impossible for them to gain useful practical skills.

How Helicopters Work

Helicopters have the unique ability to take-off, hover, and land vertically in and out of areas otherwise inaccessible for cars or airplanes. To accomplish this feat, helicopters use spinning disks of blades, called main rotors, generating aerodynamic lift supporting their weight. Figure 1 shows a typical helicopter configuration with the main rotor spinning on top of the passenger compartment powered by one or more engines. A second smaller spinning disk of blades is pointed sidewise on the tail (tail rotor) to provide directional stability. The helicopter is controlled by a trained pilot (sometimes two pilots) seated in the front of the passenger compartment in what is called the cockpit.

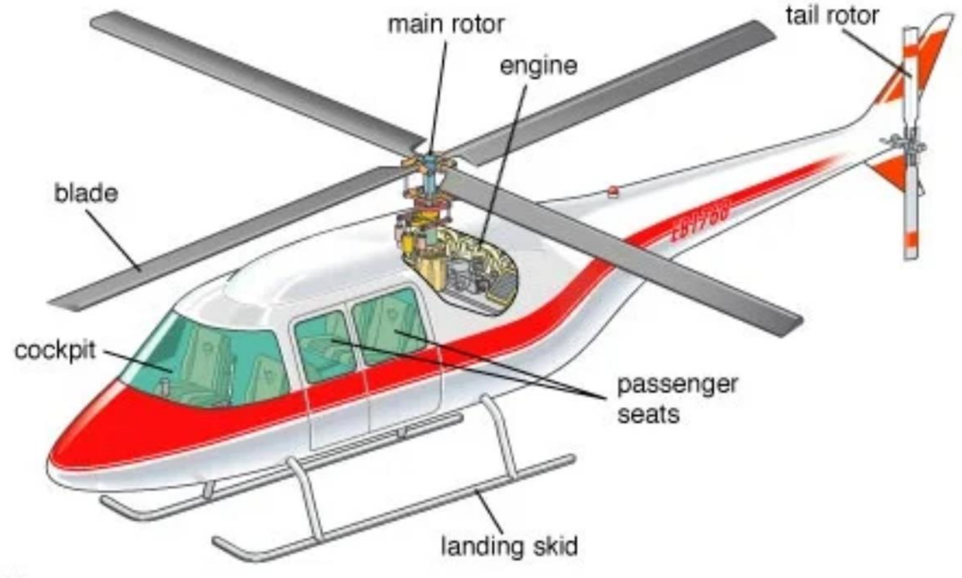

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Figure 1: Helicopter Basic Schematic [3]

The pilot controls the helicopter's behavior by making inputs to the cockpit flight controls to affect the spinning rotors [4]:

- Collective → Main Rotor: vertical lift & altitude
- Cyclic → Main Rotor: front-back & left-right velocity
- Pedals → Tail Rotor: Direction & yaw rate (or spin)
- Engine Control → Engine: Rotor Spin Speed

To legally fly helicopters in the U.S., for example, pilots must complete Federal Aviation Administration (FAA) approved training and pass written and practical examinations. [5] A typical pilot training program consists of multiple stages designed to ensure students gain the necessary knowledge, skills, and experience to become competent and certified pilots. The training begins with Ground School, where students attend lectures and complete coursework to learn theoretical knowledge about aircraft operations, such as cockpit instrumentation, flight planning, navigation, regulations, normal procedures, and emergency scenarios.

Once they pass their written exams, students transition to Flight Training, where they apply what they learned. Commonly known as "stick and rudder skills" (a term borrowed from airplanes), pilots build their practical flying by repeatedly practicing take-offs, landings, flight maneuvers, and even some mock emergencies. [6]

Modeling a Human Flying a Helicopter

Developed in 2018, Figure 2 presents a System Dynamics model representing the dynamics of a helicopter in flight with a "human-in-the-loop" making flight control inputs to change altitude and yaw rates.

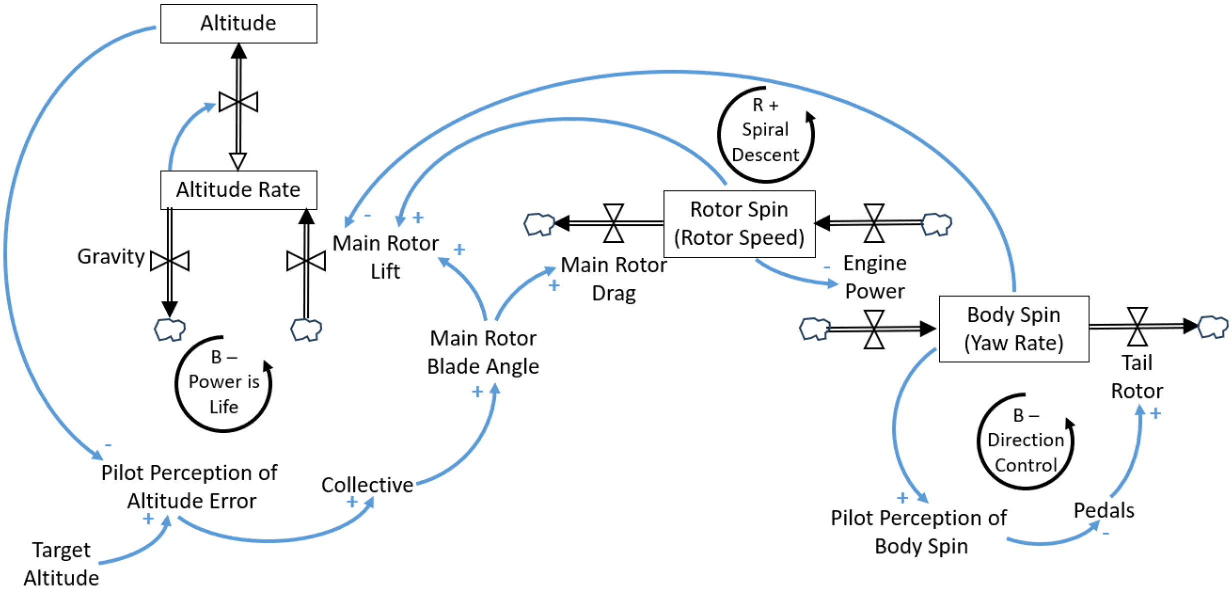

Figure 2: System Dynamics Model of a Human Piloting a Helicopter

The main rotor is depicted on the left side of the model, generating an upward Main Rotor Lift (flow), filling the Altitude Rate stock to counteract the weight of the helicopter (Gravity drain). When the Main Rotor Lift is larger than Gravity, the Altitude Rate flows into the Altitude stock, and the helicopter rises into the air. Using cockpit instruments, the pilot monitors the helicopter's altitude and pulls up (positive) on the Collective if it is too low to increase the Blade Angle, which increases Main Rotor Lift.

The other key component of the main rotor lifting the helicopter is its rate of spin, called 'Rotor Speed', shown as a stock near the middle of the model in Figure 2. Blades not only generate lift, but they also create a spinning resistance force called 'Main Rotor Drag'. Increasing the Main Rotor Blade Angle also increases the Main Rotor Drag, slowing down the Rotor Speed and thus reducing the overall Main Rotor Lift. Keeping the rotor spinning is the sole job of the engine, which monitors Rotor Speed and provides the power needed, in the form of torque, to overcome the Main Rotor Drag.

This complete loop is labeled 'Power is Life'; helicopter pilots use it to fly, maneuver, and avoid obstacles while the engine dutifully supplies the necessary power. Throughout their careers, pilots can spend thousands of hours repetitiously driving more altitude, climb, speed, payload, and maneuvering from their helicopters by pulling up on the collective to inject more power into the rotor system. For a pilot and helicopter, power is life.

However, there is a downside to adding more power because, according to Newton's Third Law, every action has an equal and opposite reaction. While the engine is applying torque to spin the rotor, it also applies torque to spin the helicopter body, but in the opposite direction. [4] This reaction is depicted as the Body Spin stock, also known as Yaw Rate, on the right side of the model in Figure 2. Whereas Main Rotor Spin is required for the helicopter to fly, Body Spin is detrimental and should always be kept to a minimum. To counteract torque from the engines, the Tail Rotor provides anti-torque to stop the Body Spin and the pilot can control it using the two cockpit pedals. If the pilot senses the body spinning, he/she pushes on the opposite pedal, adjusts the Tail Rotor anti-torque, and stops the spin (a balanced loop labeled 'Directional Control').

When Things Go Wrong

Like any mechanical system, helicopters break, and one scenario pilots must always consider is losing tail rotor thrust, which can happen in one of two ways. The first, and most likely, is commonly referred to as Loss of Tail Effectiveness (LTE), where the helicopter is mechanically sound, but the tail rotor simply loses the ability to provide thrust. This is typically caused by aerodynamic interference from the main rotor wake, its own wake ingestion, high altitudes (thin air), and/or adverse winds [7]. The best mitigation to LTE is avoidance, and pilots are trained on how to steer clear of these aggravating factors.

The second failure mode for helicopter tail rotors is much more violent, abrupt, and dangerous: a mechanical failure. Mechanical failures can occur in the driveshaft, gearbox, or blades caused by striking obstacles, poor maintenance, fatigue, or inherent defects. The tail rotor can either physically depart the aircraft or simply stop spinning, both of which result in total loss of thrust. Unlike LTE's, mechanical tail rotor failures are unpredictable and strike with little or no warning to the pilot.

Regardless of the cause, losing the tail rotor results in the helicopter rapidly developing body spin, as depicted in Figure 3. Without a functioning Tail Rotor, Engine Power fills the Body Spin stock unabated. The pilot will obviously observe the helicopter spinning, but any attempts to stop it by applying an opposite pedal will be ineffective. An unabated Body Spin quickly escalates to pilot disorientation, uncontrolled flight, and, because of the reinforcing Spiral Descent loop, loss of the Main Rotor Lift and a crash.

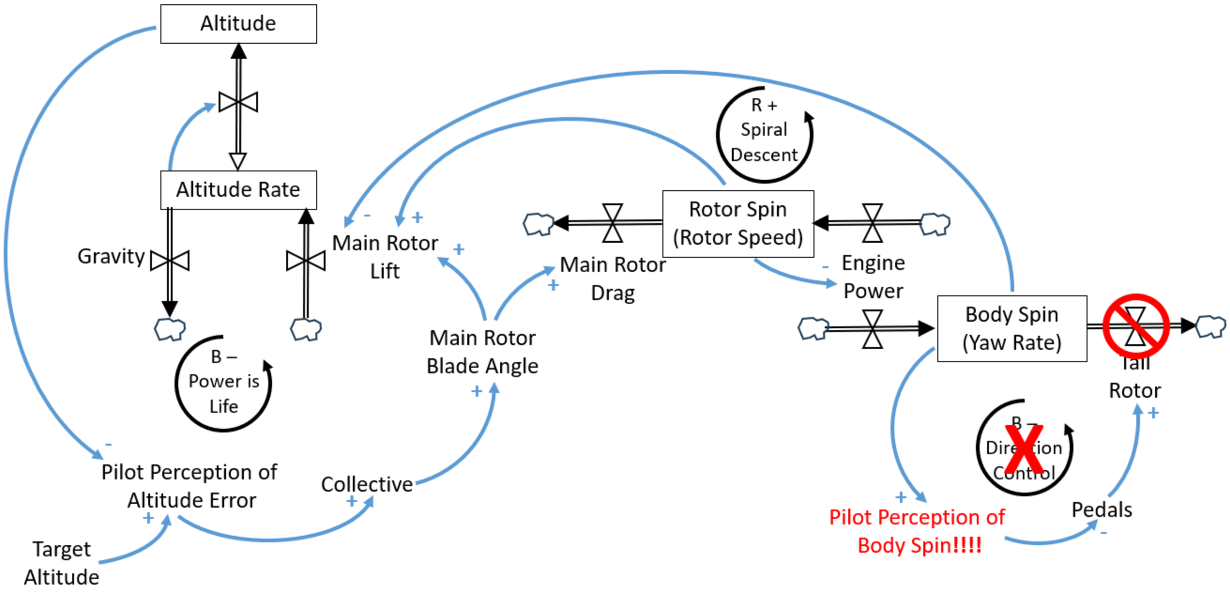

Figure 3: System Dynamics Model of a Helicopter with a Malfunctioning Tail Rotor

Correlating the Model to the Real World

When possible, validating any System Dynamics model with real-world data helps establish trust in its accuracy and applicability. For the model in Figure 3, real-world flight data from helicopters losing tail rotors is understandably hard to find. However, it can be verified indirectly with real-world helicopter accident reports from the U.S. National Transportation Safety Board (NTSB):

- On December 15, 2023, in Beluga, Alaska, a Eurocopter AS350 B3 helicopter was transporting a 1,000lb load swinging on the end of a 100ft line. During maneuvering, the line became entangled in the tail rotor causing the gearbox to separate and lose control. Per the NTSB accident report, the helicopter *"…suddenly yawed, and then started to spin uncontrollably."* The report continues, "*As the helicopter continued to spin uncontrollably, it descended in an area of tall trees and then came to rest on its left side."* [8]
- In Millen, Georgia on September 29, 2021, the pilot of a Hiller UH-12E helicopter, *"…heard a 'pop' sound [from the tail rotor gear fracturing] followed by the engine accelerating to a high rpm. According to the pilot, the helicopter began spinning counterclockwise at a high rate; …pedal control inputs had no effect. The pilot continued his attempts to counteract the helicopter's rotation [unsuccessfully] as it descended to ground impact."* [9]

Both NTSB accident reports above confirm the general causal loops of the System Dynamics model in Figure 3:

Loss of tail rotor → Uncontrolled spin → Pilot unable to counteract → Ground impact

However, other than describing the spin as a "high rate", these reports do not quantify the rates and timing. To help provide these insights, a simple set of "back of the envelope" calculations for a UH-60L Blackhawk helicopter are presented in Appendix A. Based on a Blackhawk hovering in nominal conditions, Figure 4 shows how the helicopter's Yaw Angle and Yaw Rate build after the tail rotor stops counteracting the engine torque.

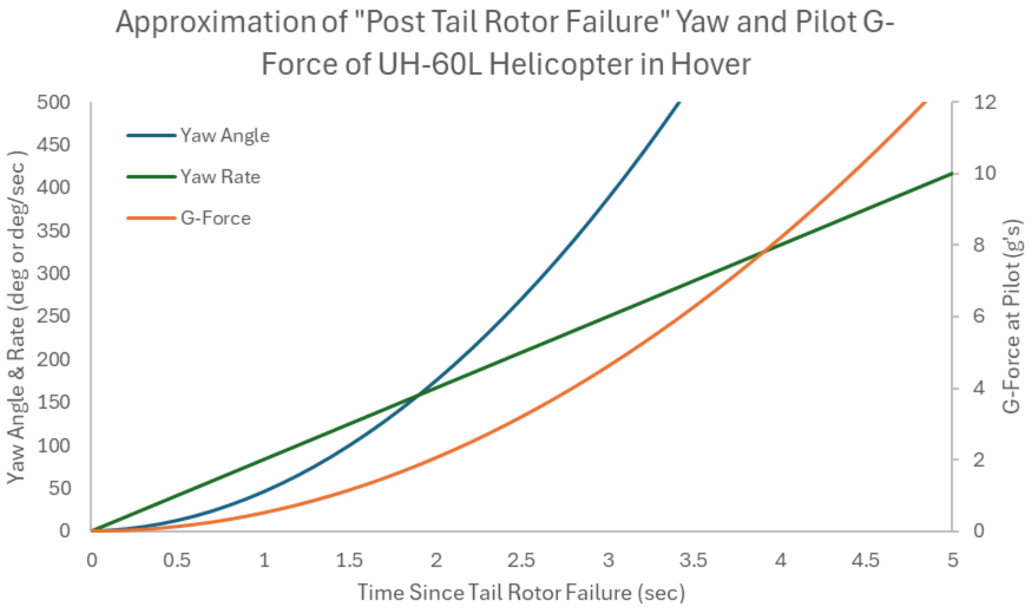

Figure 4: UH-60L Blackhawk Spin Rate & Forces After a Tail Rotor Failure (see Appendix A)

Although an approximation, Figure 4 helps illustrate trends. Just as the System Dynamics model in Figure 3 suggests, when the tail rotor fails, the helicopter spins, slow at first but steadily increases with time. Approximately 4 seconds after the tail rotor failure, the helicopter will spin one full turn every second.

Also shown in Figure 4 is the pilot G-force from the spinning helicopter. Just as children must fight centripetal g-forces trying to fling them from a spinning playground merry-go-round, a pilot will feel increasingly heavier forces as the helicopter spinning accelerates. This simple model suggests the pilot will experience 6 g's, or 6x their body weight, after just 3.5 seconds of accelerating spin. At 5 seconds, it will be more than 12 g's. Eventually, there will be a "point of no return" when the high g-forces will be too much for a human to overcome.

Blackhawk Down

As depicted in the 2001 Ridley Scott film, *Black Hawk Down* [10], Michael Durrant was in the *Battle of Mogadishu* [11] on October 3, 1993, piloting a UH-60L Blackhawk helicopter when a Rocket Propelled Grenade (RPG) destroyed his tail rotor. In his book covering the same event, *In the Company of Heroes* [12], Durrant gives a first-person account:

> *"The nose of the helicopter immediately started to spin to the right. The tail rotor on a Blackhawk counters the torque created by the main rotor system, and the pedals control the pitch of the tail rotor. As we passed through the first ninety degrees of rotation, I instinctively countered with left pedal, and I knew we'd lost it. I'll never forget looking down to make sure I was pushing the pedal, and seeing my boot jammed all the way to the floor. My body was reacting properly, but my helo was not."* [12]

This first-person account provides anecdotal validation of the causal loops of the tail rotor failure System Dynamics model in Figure 3. As far as the magnitude and the speed at which the spin rate and g-forces develop in the model, Durrant provides additional perspective:

> *"…the Blackhawk manual describes such an emergency, if you don't kill the engines right away the centrifugal force will make it physically impossible to reach up for the power control levers. I'd always thought that sounded a little extreme. It wasn't.*
>
> *Super Six-Four [helicopter call sign] started to spin so fast that the sky and ground became nothing but two blurred stripes of blue and brown in front of my eyes. It was like riding a merry-go-round and looking straight out to the side from your horse, while the teenage operator goes nuts and hauls it up to fifty revs per minute. I was hurled against my harness, my hands desperately yanking and twisting the controls, and I looked over at Ray [co-pilot] to see him fighting the force with every muscle, his gloved hands quaking as he tried to reach up for the power levers."* [12]

Again, Durrant's first-person account provides more validation about the increasing physical stresses imposed upon the pilots as they desperately work to recover the helicopter.

Stopping the Spin

As chaotic, dangerous, and seemingly desperate as a tail rotor failure is in a helicopter, there is a simple and effective recovery method. As Michael Durrant briefly hints at in his account above, if an unabated engine is causing the helicopter to spin uncontrollably, then stop the engine. In a normal operating helicopter, as depicted in Figure 2, engines are essential for flight as the driving force behind the "Power is Life" causal loop. However, without the tail rotor, the downside of engine power outweighs the upside and must be removed from the system before it causes irreparable harm.

Obviously, stopping the engine during a flight presents a new set of issues, namely the decrease in rotor speed and loss of the main rotor Lift. To counteract this, the pilot must immediately and simultaneously push down on the collective to reduce the main rotor drag and preserve rotor speed. In the 'Emergency Procedures' section of the UH-60L Operator's Manual (Chapter 9), if a loss of the tail rotor occurs, the pilot is instructed to make an "immediate" reduction in collective followed by switching the engines off [13]. If the pilot performs these recommended actions quickly enough, the helicopter will stop spinning, but unsurprisingly, without engine power, it will also begin to descend. If in a low speed/hover condition, the pilot does their best to manage the helicopter as it settles to the ground. However, if in forward flight, the pilot can settle the helicopter into a stable and controllable state of unpowered descent to landing, called 'autorotation'.

Autorotation in a helicopter can best be described as reversing the airflow through the main rotor to spin the blades. Like blowing on a child's pinwheel, the airflow passing through the bottom of the main rotor as a helicopter descends causes the blades to spin. Without an engine, the "Power is Life" loop disappears and the collective now has a different function: controlling rotor speed [4]. This new causal loop is depicted in Figure 5 and labeled "Autorotate".

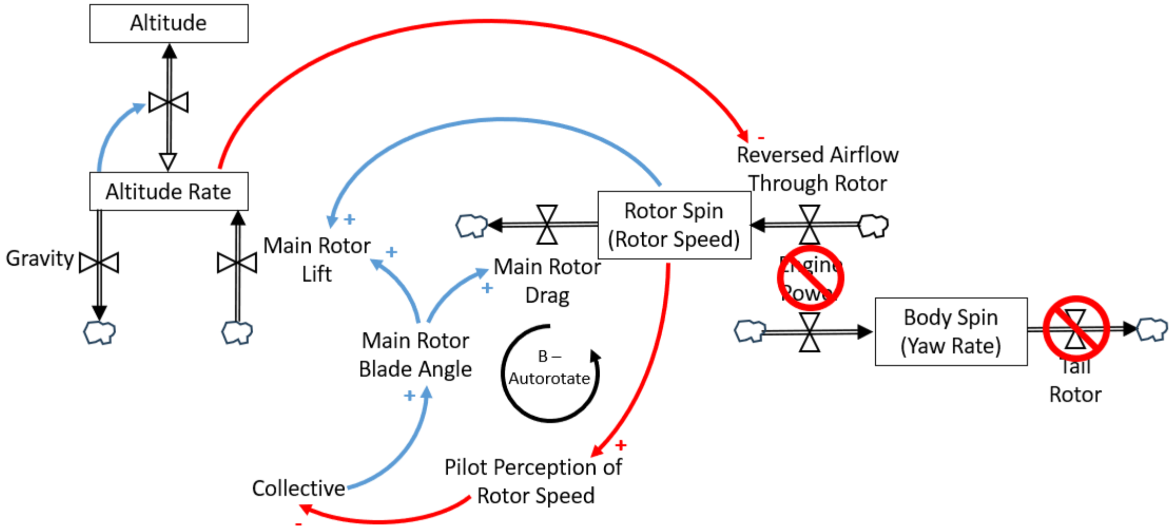

Figure 5: System Dynamics Model of a Helicopter in Autorotation

The Recovery is Simple, but Challenging

Pilots learn the procedures to survive emergencies, including tail rotor failures during training. The challenge is taking the correct action before the uncontrolled spinning becomes unmanageable, a timeframe measured in seconds. Or, as the operator's manual suggests, "immediately" [13]. This is further complicated by the "inertia" from their overdeveloped "Power is Life" function of the collective.

After spending thousands of hours throughout their flying careers using the collective to drive "Power is Life", the pilot must counterintuitively reverse the direction of their collective within a few seconds.

Before the pilot acts to autorotate, they must recognize and assess the situation through a sequence of events, as depicted in Figure 6. Although the helicopter operator's manual emphasizes the pilot must act "immediately", [13] in reality, it takes the human mind "processing time" to complete all the steps, shown as "Delay". Furthermore, there is a complicating factor of the pilot's strong and well-developed "Power is Life" instinct, potentially adding delay to the decision.

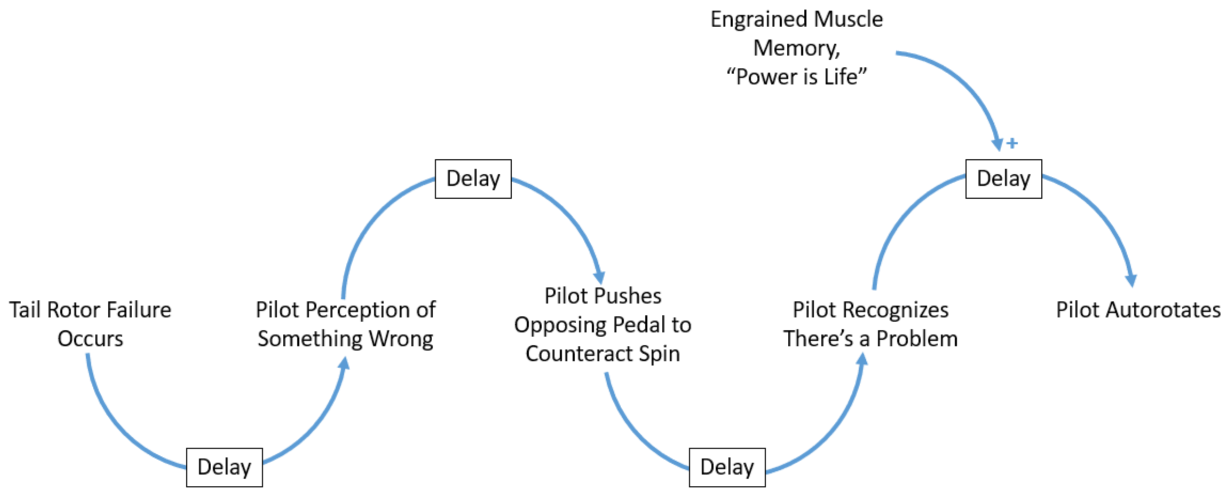

Figure 6: Sequence of Human Pilot Actions Between Emergency and Action

Does the total time, from tail rotor failure to pilot-initiated autorotation, fall within the window of human ability, i.e., before the g-forces are too high? Michael Durrant's firsthand account provides an anecdotal clue when he recalls, "*As we passed through the first ninety degrees of rotation, I instinctively countered with left pedal*". [12] Referring back to the plot in Figure 4, Durrant's UH-60L is estimated to pass 90 degrees of rotation (Yaw Angle) at approximately, 1.4 seconds. In other words, it required Durrant 1.4 seconds to perceive there was a problem (RPG strike!) and push the opposing pedal to counteract the spin. How much longer would it take Durrant to process the second half of the sequence and autorotate? Does Durrant's extensive experience flying "Power is Life" add friction to slow down the decision process? It's not known, but if Durrant takes another 1.4 seconds, for a total of 2.8 seconds, Durrant and his co-pilot would be exerting against 4 g's, or 4x their body weight, which again, aligns with their struggle in the cockpit, "*I was hurled against my harness, my hands desperately yanking and twisting the controls, and I looked over at Ray [co-pilot] to see him fighting the force with every muscle…*". [12]

As described above, helicopter training consists of ground school, in the classroom, and flight training, in the aircraft. Surviving a tail rotor failure will be covered in the classroom; however, it is impossible to safely demonstrate it in the aircraft. There is no safe and practical method to disable the tail rotor in a helicopter and as such, student pilots never gain the practical skills to practice the theory they learn in the classroom. If an actual tail rotor emergency occurs, it will be the first-time pilots, overwhelmed by the spinning and oppressive g-forces, will try to apply what they learned in the classroom before it is too late.

It's Time to Think Fast, not Slow

Pilot instructors have long understood how students learn is as important as what they learn. The reason is because the path to gaining knowledge determines how quickly it can be recalled. Daniel Kahneman captures this in his book, *Thinking, Fast and Slow* [14], by describing humans as essentially having "two brains", System 1 and System 2. System 1 thinking is fast, intuitive, and emotional. System 2 is slower, more deliberative, higher effort, and more logical. System 1 thinking learns by doing an activity repeatedly and is how humans learn to walk, ride bicycles, and roller skate. System 1 requires repetition to build competency, but once mastered, the knowledge, or "muscle memory", can be recalled near-instantaneously. In contrast, System 2 thinking is non-reactive and ideal for problem solving, abstract thought, and deliberation, and can learn passively from listening, reading, and watching, such as in a classroom. System 2 thinking is useful for doing tax returns, solving problems, and writing poetry but operates much slower than System 1. [14] The two Systems of thinking complement each other when working together, but skills and knowledge do not transfer from one to the other. For example, if someone is hoping to learn how to roller skate by only reading "how to" books and watching videos, they will be in for a rude surprise the first time they strap on a pair of skates.

While in pilot training, students develop System 2 knowledge in ground school to learn how aircraft systems work, to read navigation charts, and to understand federal regulations. But when they are in flight school, pilots use System 1 thinking to develop their "stick and rudder" skills while practicing maneuvering flight. With time, a pilot's inputs to the flight controls become fast-acting and confident reflexes requiring little thought and no hesitation. However, if they have never practiced a tail rotor failure, it will be like strapping on roller skates for the first time after only reading "how to" books in ground school. Worse, they have one chance and only a few seconds to figure it out.

Using System Dynamics to Change Human Behavior

If training tail rotor failures in the helicopter is too dangerous, how do pilots develop the practical skills needed to survive? First introduced for helicopters in 1999 [15] (note: this is after Michael Durrant's incident in Mogadishu), FAA-approved flight simulators provide a safe and highly realistic alternative to training in the aircraft. As shown in Figure 7, flight simulators are designed with exact cockpits, replica flight controls, high-definition wrap-around virtual reality, and large motion reaction systems. Driving the realism in these high-tech machines are high-powered computers running thousands of System Dynamics models simultaneously. The flight characteristics of the helicopter, the reaction to the flight controls, the dozens of instruments in the cockpit, and even the simulated sounds of the engines are all simulated through multitudes of causal loops, stocks, and flows. System Dynamics is a perfect method to iteratively solve dozens of 2^{nd} order non-linear differential equations, hundreds of times per second, to model the complex physics of swirling airflow around the high-speed rotating blades. The engine, rotating rotors, and airframe models all interact with each other, in a "system of systems", to generate the appropriate helicopter altitude, speed, and spin, both in normal and abnormal conditions. [16] To ensure the highest level of accuracy, the System Dynamics models are designed, tested, and validated with real-world flight test data. [17]

The FAA regulates the design, testing, and operations of modern flight simulators and when certified at the highest level of fidelity and accuracy (called 'Level D'), can remove 100% of the flight training from the helicopter, in the eyes of the FAA. [19]

Figure 7: Full Flight Simulator [18]

Unlike aircraft, flight simulators can be used to safely and repeatedly demonstrate and practice emergency scenarios. In a flight simulator, helicopter pilots, for the first time, can experience a tail rotor failure and practice reversing the collective. With repetition, the pilot's ability to process the emergency will move from their slow System 2 thinking to their instinctive System 1, drastically reducing their reaction time.

Twenty-five years after introducing the first FAA helicopter flight simulator, the industry has made remarkable progress in adopting and incorporating this life-saving flight technology into pilot training. Air Methods, a leading provider of EMS helicopter services, states on its website:

> *"Level D simulators are the gold standard of flight training because they provide a realistic training environment. Our pilots get the closest experience to actual flying in the simulator and it's the only non-aircraft training method accepted by the FAA.*
>
> *There are several advantages for pilots when training in a level D simulator. For starters, pilots can train dangerous scenarios like engine failures and <u>loss of tail rotor thrust</u> without risking lives. They can also train better for emergencies and incidents by repeating…providing effective training in less time."* [20]

The technology and the System Dynamics models in flight simulators continue to develop and add higher levels of realism. Unfortunately, due to their high cost and limited accessibility, not all helicopter pilots have access to this life saving technology.

Case Study: Rewiring the Human Brain

In 2008, the author, Steve, was the engineering technical lead for helicopter flight simulator development at FlightSafety International, a wholly owned subsidiary of Berkshire Hathaway and leading provider of flight simulators and pilot training. Steve was finalizing the details of a new Bell TH-1H helicopter for the U.S. Air Force [21], one of many flight simulators developed for the U.S. military as part of their new Flight School XXI pilot training program. [22] At this time, flight simulators were still considered a "new technology", and the Air Force was anxious to incorporate the TH-1H simulator into their pilot training program.

Steve was working with an Air Force Instructor pilot, named "Joe", who oversaw the final acceptance testing of the flight simulator to confirm its accuracy. Joe was especially interested in the "tail rotor loss" malfunction so he could safely train airmen how to recognize and recover from this dangerously chaotic scenario. Before testing it in the simulator, Joe described to Steve his expectations of what happens when a TH-1H loses a tail rotor. Joe described how he expected the simulator to spin, slowly at first but building quickly, and how he taught his students, in the classroom, to quickly reverse the collective and autorotate. With the correct collective input, Joe expected the simulator to stop spinning, allowing the students to regain full control and autorotate to a safe landing. However, if the students did not make the correct recovery inputs, or were too slow, then the simulator would flash red and freeze in place signifying a simulated crash.

The simulator was set up to test the "tail rotor loss" scenario with Joe in the cockpit flying and Steve behind him at the "Instructor's Station" controlling the simulator. Steve pushed the button and the simulated tail rotor stopped producing thrust. The motion system suddenly heaved the simulator and the synthetic visual scene of the outside began to spin, eventually blurring as the spin accelerated. As the seconds ticked by, the spin rate increased, the motion heaved more aggressively, and Steve waited for Joe to reverse the collective to "save" the simulator, just like they briefed. Instead, Joe pulled up on the collective, opposite of what they discussed, and the simulator quickly flashed red and froze, ending the test as a 'crash'.

The person responsible for teaching other Air Force pilots how to survive tail rotor failures just crashed because he did the opposite of what he teaches. But to be fair, this was the first time Joe's System 1 thinking had ever "seen" a tail rotor failure, and he reverted to what he knew best, "Power is Life". His System 2 thinking was simply too slow to intercede. Fortunately, Joe recognized this was exactly why he needed the flight simulator.

The simulator was reset, and Joe tried again with the same result. And then again, and again, and again. With repetition, Joe started to learn how to reverse his collective, too slow at first and still crashing, but quicker on each attempt. After many attempts, Joe snapped the collective down immediately disengaging the engine, and stopped the simulator from spinning. Joe gently autorotated the simulator to a controlled landing. Joe was satisfied, the Air Force accepted the simulator, and the TH-1H flight simulator was put into service training new pilots.

After the project, Steve moved on to other helicopter flight simulator programs and Joe returned to his job as a flight instructor, but now using a new, state-of-the-art TH-1H flight simulator. A time later, Steve reconnected with Joe and learned about an accident he had in the helicopter.

On June 30, 2009, Joe was piloting a TH-1H helicopter with two other crewmen on a night mission over the Conecuh National Forrest of Alabama. Flying fast, low, and in the dark, Joe's worst nightmare occurred: his aircraft "…experienced a loss of tail rotor thrust, yawed right, and entered into an uncontrollable right rotation…" [23]. This scenario is scary enough in the daylight, but tumbling uncontrollably in the complete darkness must have been terrifying. In a follow-up email to Steve, Joe wrote:

> *"The experience gained during the development of the TH-1H simulator gave me exceptional in-depth knowledge of the aircraft as well as extensive experience flying in malfunction scenarios that I would never have been able to experience in the actual aircraft. During testing I was exposed to many tail rotor malfunctions resulting in both controllable landings and uncontrollable spins. My experience during testing, especially in tail rotor malfunctions, allowed me to better control the aircraft during my mishap. Even though my malfunction occurred while I was wearing night vision goggles (never practiced before), my previous experience in an uncontrollable spin in the simulator allowed me to INSTINCTIVELY make control inputs that resulted in the survival of my crew and myself."*

Even the official government accident investigation report included a comment about Joe's piloting, "Given the flight parameters where the tail rotor lost thrust, he [Joe] performed admirably to land the aircraft without fatality." [23]

Using System Dynamics to simulate the complexities of a flying helicopter, the chaos of a system failure, and the behavior of a human reaction, holistically as a system of systems, Joe's brain was "rewired" to save himself along with two other crewmen.

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Appendix A: Approximating UH-60L Helicopter Response After Tail Rotor Failure

This appendix uses publicly available data and basic physics equations to present a simple spin model of UH-60L Blackhawk helicopter during a tail rotor failure. In this scenario, the engines are providing the power (torque) to sustain hover and per Newton's 3rd Law, are also applying an equal but opposite torque to the body causing it to spin. This approximation assumes zero losses or drag.

Aircraft & assumed flight parameters [24] [13] [25]:

Assumed Weight:	18,000 lbs
Yaw Moment of Inertia (I_{zz}):	37,200 slug-ft^2
Engines (x 2):	GE T700-701C
Engine Horsepower (HP):	1,662 shp (each)
Engine Shaft Speed (N_E):	20,900 rpm
Main Roto Speed (N_R):	258 rpm
Distance from Center of Gravity (c.g.) to Pilot (X_P):	7.8 ft
Pressure Altitude:	Sea Level
Outside Air Temperature:	15 deg C
Flight Phase:	Out-of-Ground-Effect (OGE) Hover

For the flight condition described above, reference the UH-60L Operator's Manual [13] to find the amount of engine power required:

Engine Power Setting (E_{PCT}) = 80%

Engine Power Required for Hover (HP_{Hov}): HP x E_{PCT} = 1,662 x 80% = 1,330 shp (each)

Using the following equation for horsepower, find the equivalent total engine torque (2 engines):

$$T_E = 2\left(\frac{HP_{Hov} \times 5252}{N_E}\right) = 2\left(\frac{1330 \times 5252}{20{,}900}\right) = 668 \text{ ft-lbs}$$

Translate the torque at the engines, through the transmission, to the main rotor mast:

$$T_{MR} = T_E\left(\frac{N_E}{N_R}\right) = 54113 \text{ ft-lbs}$$

Using the equation below, find the yaw angular acceleration (α) of the body spin:

$$\alpha = \frac{T_{MR}}{I_{ZZ}} = 1.5 \text{ rad/sec}$$

Integrate the angular acceleration, over time, *t*, to find the equations for yaw rate (r) and heading (ψ):

$$r = r_0 + \alpha t \text{ (rad/sec)}$$

$$\psi = \psi_0 + r_0 t + \frac{1}{2}\alpha t^2$$

Finally, approximate the spin induced acceleration experienced by the pilot (a_P) using the yaw rate (r) and the distance between the aircraft c.g. and pilot (X_P):

$$a_P = \frac{r^2}{X_P}$$