Houston Community College

Hog Aerial Mitigation System

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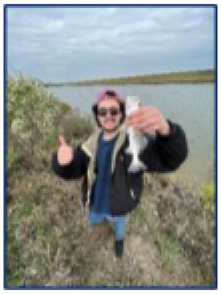

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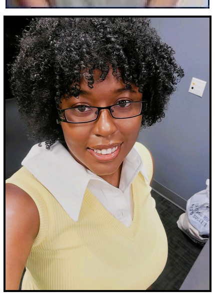

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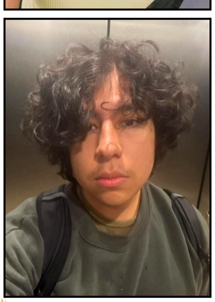

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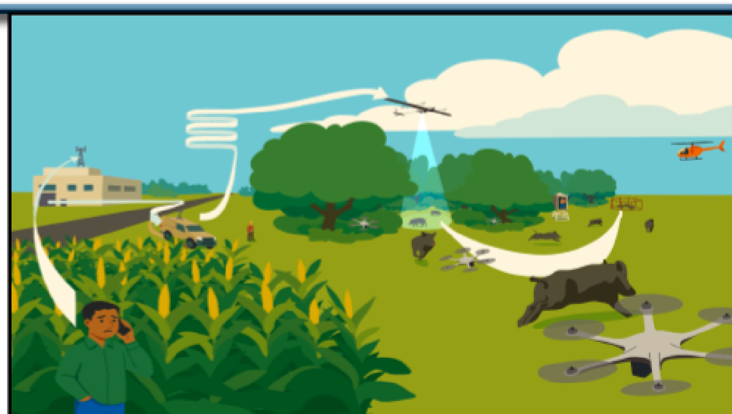
  - Hexacopter drone swarm
  - AI Computer Vision and Predictive Analysis
  - Ground Control Station
  - Operations Call Center



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- Student Team - Houston Community College - **HAMS Team**
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  - **Reymundo Roman** (Sophomore, Aerospace Engineering) | Hardware Systems, Deployment
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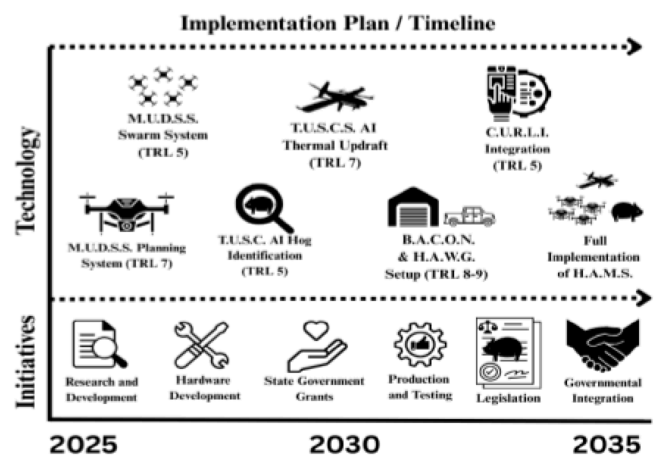

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H.A.M.S.	Hog Aerial Mitigation System
H.A.W.G.S.	Hog Aerial Watch and Ground Station
T.U.S.C.	Thermal Updraft Surveillance Craft
M.U.D.S.S.	Multirotor Unmanned Drone Shepherding Swarm
C.U.R.L.I.	Computer User Regulated Live Interface
B.A.C.O.N.	Broad Area Control Operations Node
TRL	Technology Readiness Level
FAA	Federal Aviation Administration
UAV	Unmanned Aerial Vehicle
IR	Infrared
AR	Aspect Ratio
LDR	Lift-to-Drag Ratio
VTOL	Vertical Take-Off Landing
FOV	Field of View
MPS	Movement Prediction System
LSTM	Long-Short Term Memory
TDS	Thermal Detection System
CONOPs	Concept of Operations
AI	Artificial Intelligence
SLEAP	Social Leap Estimates Animal Poses

0.0 Abstract

As the population of the globe increases, so does the demand for food. Modern agricultural practices work to meet this demand, but pests threaten humanity's ability to do so. Feral hogs represent an acute threat to our global agriculture. They trample crops, pollute water sources, damage infrastructure, and spread disease to people and livestock. Their population has grown exponentially to uncontrollable numbers, and current management methods barely slow their unstoppable spread. And while feral hogs present a problem worldwide, with populations on every continent except Antarctica, our team takes special interest in their effects in Texas, where the hog population is the highest in the United States. Our proposed system, the Hog Aerial Management System (H.A.M.S.), aims to support the removal of feral hogs in the areas where current methods fail. Our system uses available and upcoming technologies such as AI computer vision, autonomous drone piloting, thermal utilization by UAVs, and sonic pest deterrents to identify hogs and flush them out. We also present a proposal for legislation to support this system and decrease the inefficient use of resources within hog management.

1.0 Situational Assessment

Feral swine, also known as razorbacks, wild pigs, feral hogs, or by their Latin name Sus scrofa, are descendants of escaped domestic pigs and purposely released Eurasian wild boar that were spread across the world by European explorers [1]. Since then, the populations of these destructive and dangerous invasive pests have rapidly grown to uncontrollable levels. They can now be found extensively in Europe, North America, Southeast Asia, and Australia, as well as parts of Africa, Central and South America, and the Pacific Islands [2]. They have negatively impacted the economy, environment, and public health in the areas where they have established themselves, and for these reasons, hog populations need to be managed throughout their nonnative range.

1.1 Hog Background & Behaviour

Feral swine reproduce at staggering rates. A sow (female hog) reaches sexual maturity around 1 year of age, after which she can enter estrus every 18-24 days [19] and is able to have 2 litters of up to 12 piglets per year [20]. This quick reproductive cycle has led to a mean annual growth rate of 0.32, allowing feral swine to quickly take over [12]. In just 30 years, hog populations have spread from just 17 US states in 1982, to 38 states and 43% of US counties in 2018 [3]. The current US swine population sits at over 6 million and is expected to keep growing. These massive populations of hogs cost the U.S. $1.5 billion in damages and management costs, $750 million or more of which is attributed to agricultural damage [3]. In 2004 in the Edwards Plateau and the Rolling Plains regions of South Texas, annual property damage caused by feral pigs averaged more than $10,000 per property owner, a figure that has only increased since [21]. Feral hogs cause these damages through their rooting behaviors that destroy pastureland, by their consumption of food crops such as rice, soybeans, and corn, through damage to farm equipment, and even occasionally through predatory behaviors towards young or small livestock [22]. In addition to the massive agricultural damage they cause, feral swine also represent an acute biosecurity risk. Hogs are known to be hosts to more than 30 diseases and 40 types of parasites that can affect humans, livestock, and wildlife [23]. Models indicate that an outbreak of just one of these infections, foot-and-mouth disease (FMD), from feral hogs to livestock would result in a minimum of $7.5 million and a maximum of $5.8 billion in damage via loss of livestock in one state alone [24]. Additionally, feral hogs have devastating impacts on the ecosystems where they are prevalent. They root through, wallow in, and trample the soil, they pollute water sources, their opportunistic omnivorous nature puts them in competition over food with many native species. These destructive behaviors of feral hogs have led to the decline of 672 taxa across the globe and have been the direct cause of the extinction of at least 14 species [26].

Due to the massive destructive effects of these vermin, several organizations have dedicated their efforts towards the management of feral hogs. The United States Department of Agriculture Animal and Plant Health Inspection Service runs the National Feral Swine Damage Management Program, which is the largest program of its kind. This organization provides millions of dollars in funding annually to dozens of national, state, and local hog management organizations. They also cooperate with international organizations, conduct community outreach and education, do research into hog management and biology, and provide hog removal services that, in 2018, removed 30,000 hogs from the wild [3]. Despite the efforts of these 5 organizations, it is up to property owners to decide how to, or even if they are going to, deal with hogs on their property. The rise in the feral hog population has led to the creation of thousands of private companies that provide specially catered hunting trips to paying customers. While many believe that any way that hogs are being killed and removed from the wild is a good thing, this creates a conflict of interest that leads to the further spread of the hog epidemic [6] [28]. Hog hunting companies, once the population of hogs on their land has been reduced, import more hogs from higher density areas and promote the breeding of those hogs on their property to maintain their business model. Some of these pigs, using their intelligence and digging capabilities, escape and lead to an outbreak in the area [4]. To address this, Texas implemented regulations within the Texas Animal Health Commission that placed limitations on transportation of feral hogs, limiting it only to boars (male hogs) and requiring certain fencing [5]. Despite this, feral swine are still frequently illegally transported, and resources are not provided to properly enforce these laws [6].

1.2 Use Case

Organizations and individuals utilize non-lethal methods such as deterrence, attraction, restriction of food and water sources, and the construction of fences. But lethal methods such as the use of toxicant bait, hunting, aerial gunning, and trapping have proved to be far more effective [7] [4]. Rarely, drones are used, but mostly for locating hog damage [11]. By far the most effective methods for managing feral hogs have been trapping and aerial gunning. Trapping, on average, costs between $14.32 to $121 per hog [4], however their efficacy is reduced if a sprung trap does not capture the entire sounder (group of feral swine), since the surviving pigs will learn to avoid traps in the future [8]. Shooting feral swine from a helicopter, known as aerial gunning, provides a cost per pig of $7.50 to $40.06 [9]. This method is extremely effective in open environments with high pig population densities, but due to the excessive cost of helicopter operation, the effectiveness drops dramatically in areas that have a low hog population density or are highly vegetated. While these methods have been effective in addressing immediate threats after damage has occurred and somewhat slowing the growth of the hog population, they have not been able to sufficiently reduce hog populations to prevent damage. This has led to the prevailing opinion amongst experts that it is not possible to completely eliminate feral swine from the wild [6] [10] [11]. There is a clear need for advancements in feral hog management. Experts estimate that at least 32% [12] to 50% [11] of hogs need to be culled each year just to maintain the current population, and despite our current best efforts, the hog population continues to grow. Management methods fail when hogs become inaccessible due to terrain challenges, when they use their intelligence to avoid and adapt to culling attempts, and when hog densities are too low for current management solutions to be economically feasible. Given the adaptability and rapid expansion of feral hog populations, it is crucial to implement innovative and efficient management solutions.

1.3 Concept of Operations

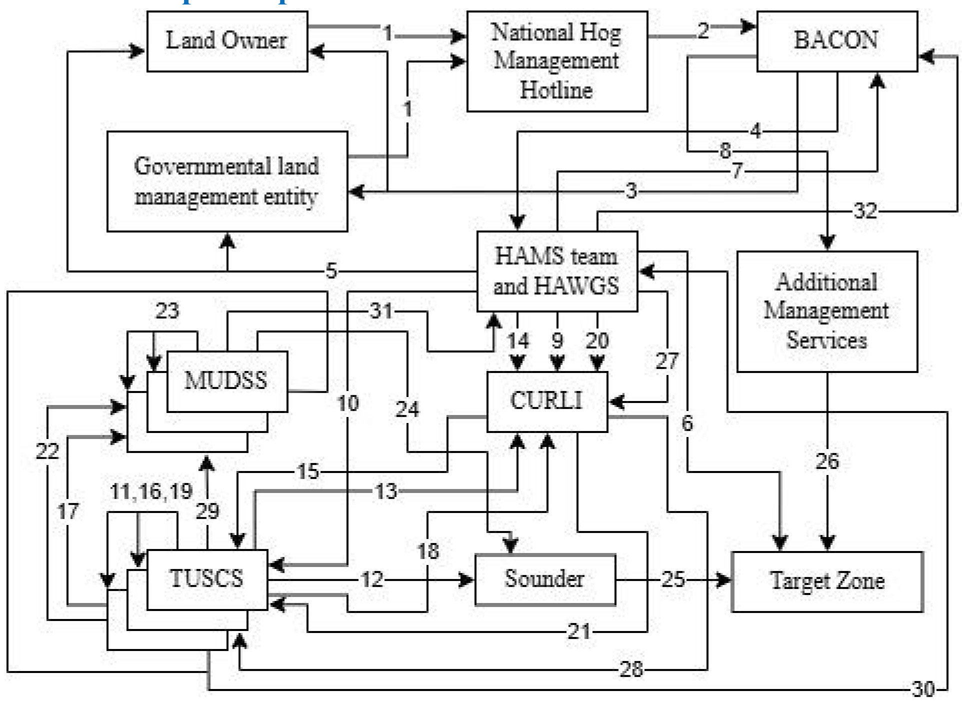


Figure 1.3.1 Concept of Operations Diagram

Figure 1.3.1 shows the concept of operations for the Hog Aerial Mitigation System (H.A.M.S.). The steps are as follows:
1. When feral hog activity is detected, either on private land or on public land managed by a governmental entity, a call is made to the national hog management hotline. **2.** The national hotline connects the caller to their regional broad area control operations node (B.A.C.O.N.) **3.** A representative collects relevant information to confirm the hog activity. **4.** Once hog activity has been confirmed, a H.A.M.S. team is organized to respond to the situation. **5.** The H.A.M.S. team establishes a hog aerial watch ground station (H.A.W.G.S.) to serve as a base of operations and begin surveying the area. The team uses their expertise in feral hog behavior to predict their likely locations and movements. **6.** The team chooses a target zone where the feral hogs will be herded to and killed or captured. The team determines the most effective method of hog management: trapping, aerial gunning, or ground gunning. **7.** Once a preferred method of hog management has been chosen, the team's needs are communicated back to B.A.C.O.N. **8.** B.A.C.O.N. managers coordinate additional management services for the H.A.M.S. operation, whether that be having a helicopter on standby or delivering more traps to the team's location. **9.** Using the Computer User Regulated Live Interface (C.U.R.L.I.), the H.A.M.S. team uses GIS software to designate a search area **10.** The H.A.M.S. team deploys the Thermal Updraft Surveillance Craft (T.U.S.C.). These fixed wing UAVs implement the utilization of thermals (rising columns of warm air) to extend flight time, perform autonomous search of the designated area to identify hogs using AI computer vision, and GPS tracking of the hogs. **11.** The T.U.S.C.s communicate wirelessly with one another to help increase the effectiveness of the thermal utilization. **12.** The T.U.S.C. identifies a sounder. **13.** The

T.U.S.C. sends imagery of the suspected sounder to the C.U.R.L.I.. **14.** The H.A.M.S. team verifies the sounder. **15.** Through the C.U.R.L.I. interface, the H.A.M.S. team activates the Multi Rotor Unmanned Shepherding Swarm (M.U.D.S.S.) **16.** The T.U.S.C.s, which carry the M.U.D.S.S. drones for increased deployment range, congregate over the sounder. **17.** The T.U.S.C.s release the M.U.D.S.S. **18.** The T.U.S.C.s form a signal relay chain between the M.U.D.S.S. and the H.A.W.G.S. **19.** One T.U.S.C. remains hovering over the sounder and M.U.D.S.S.. **20.** The H.A.M.S. team, using the C.U.R.L.I., control the flight formation of the M.U.D.S.S. to best surround and corral the feral hogs. **21.** The T.U.S.C. communications chain relays the commands. **22.** The M.U.D.S.S. receives the commands. **23.** The M.U.D.S.S. drones communicate their position and environmental data to the rest of the swarm, and using this data and the commands received, they coordinate their flight paths to their destinations. **24.** The M.U.D.S.S., forming a u-shape around the sounder, uses sonic devices to control the sounder's direction of travel. **25.** The sounder is pushed into the target zone. **26.** The selected hog management method is implemented, and the hogs are culled or removed. **27.** The H.A.M.S. team uses C.U.R.L.I. to activate the return signal. **28.** The return signal is relayed through the T.U.S.C.s. **29.** The return signal is received by the M.U.D.S.S.. **30.** The T.U.S.C.s autonomously return to the H.A.W.G.S.. If there is enough battery remaining, then the M.U.D.S.S. drones do so as well. **31.** The M.U.D.S.S. that were unable to fly back to the H.A.W.G.S. are collected by the H.A.M.S. ground team. **32.** The H.A.M.S. team packs up the H.A.W.G.S. and returns to the B.A.C.O.N..

1.4 Hog Aerial Mitigation System

The H.A.M.S is made up of two drone aircraft as seen here in Table 1.3.1. Since the original proposal, we have fully fleshed out the system architecture, trying out new ideas and conducting trade studies to make the system feasible.

Table 1.4.1: Technical System Overview

Parameter	T.U.S.C.	M.U.D.S.S.
L x W x H	180" x 40" x 20"	12" x 12" x 6.25"
Weight	20 lbs + 11 lbs payload	3.9lbs
Technologies	**AI Computer Vision, Autonomous Flight, MPS, TDS, Telemetry, VTOL,**	**Autonomous Flight (Partial), Telemetry, Object Detection, Sonic Device**
Operation Use	**Network Relay, Hog Identification**	**Hog Deterrence and Herding**

T.U.S.C. modeled after Stalker XE [X], M.U.D.S.S. modeled after [44]

1.5 Software Systems

AI enables autonomous operation and allows flight operators to focus on their primary tasks. Both the T.U.S.C. and the M.U.D.S.S. will be trained through simulation and reinforcement learning prior to deployment. By leveraging a sequential LSTM architecture and SLEAP analysis of GPS time series data, the system aims to achieve predictive analysis of wild hog behavior.. This predictive capability has potential use-cases in research and could lead to more successful operational outcomes through a better understanding of wild hog behavior.

2.0 Implementation Analysis

The implementation of H.A.M.S. prioritizes simplicity of operation and the strategic use of technology, particularly AI. While AI provides core capabilities, the system incorporates a human-in-the-loop approach to manage complexity and ensure operational oversight. This philosophy of balanced automation and human involvement facilitates the exploration of complex and innovative ideas as AI handles more granular tasks.

2.1 Legislation

Our team will propose legislation that targets three essential objectives, improvement of the approach to hog mitigation, enforcement of preventative measures, and an incentive for landowners. H.A.M.S will be proposing a centralized governmental organization that managers hogs nationally. Additionally, current laws against illegal hog transportation are not properly enforced. To address this, we will implement online training modules that display signs of illegal pig transportation and outline protocols. Finally, we must provide an incentive for landowners beyond the positive effects of hog mitigation. Land owners will receive a refundable tax credit when HAMS is allowed to operate on their property. A refundable tax credit allows all, including those who don't owe much in taxes, to benefit. The refundable tax credit will only be provided once a large amount of hogs are detected in a county rather than individual land, preventing abuse of the incentive.

2.2 Expected Improvement

Current systems in use for hog removal are ineffective because of the harsh terrain that hog hunters cannot reach. Hogs being very adaptable creatures, they can survive in most habitats and removal efforts have a delayed response time. We can expect to see a large improvement to the wellbeing of agriculture. The immediate and autonomous nature of the system allows for reduced response times which give hogs less time to evade capture or relocate. This with the adaptive and silent capabilities of the TUSC and MUDSS, prevent hogs from adapting to the deterrent systems, which is a common flaw in current methods. Collectively, these improvements will increase operational efficiency and coverage for surveillance.

2.3 Return on Investment

During the research phase, a baseline for the data on annual hog elimination as well as a true population rate of increase will be determined. Publicly available data on annual hog elimination as well as the population's rate of increase is inconsistent with a wide range. Secondly, during the development stage, HAMS's performance will be assessed and the number of hogs eliminated by one system will be quantified. HAMS will utilize this data by projecting the population of hogs over several years and determining how long it will take the system to reach a return on investment. Analyzing location data against damage to property will also help determine a more precise ROI.

2.4 Limitations & Constraints

The cost of weight and energy for communication systems is a current limitation for the MUDSS along with the terrain that the system would operate in. Due to the optimization for speed, MUDSS must be lightweight, making them unable to carry large network payloads that would allow them to communicate to base directly and the dense forest limits certain communication systems. To allow for information and communication between the HAWGS and MUDSS during deployment, the TUSC has an onboard relay system. MUDSSs communicate between each other and relay this information to the TUSC, which in turn relays the information back to the people at the HAWGS, where they can process and be alerted of any events. This solves the problem of having too short range communications and high speed data transfer.

3. Path to Deployment

H.A.M.S. is designed for deployment by 2035 by utilizing high technology readiness levels and simplifying research and development. A streamlined implementation process will further lower the complexity required for efficient system deployment.

3.1 Timeline

Figure 3.1.1 outlines the projected deployment timeline for H.A.M.S. through 2035, detailing the initiation of technological developments and strategic initiatives aimed at advancing the system. The program will begin with a focused research and development phase to ensure seamless integration of software, computational components, and drone platforms. This will be followed by hardware development, during which core technologies, like communication systems, will be integrated. With the support of state government funding, production and testing will begin, enabling the implementation of systems like B.A.C.O.N. and H.A.W.G.s. As testing progresses, additional components such as C.U.R.L.I. will be incorporated. Continued legislative engagement and coordination with government agencies will position H.A.M.S. for federal adoption and nationwide deployment.

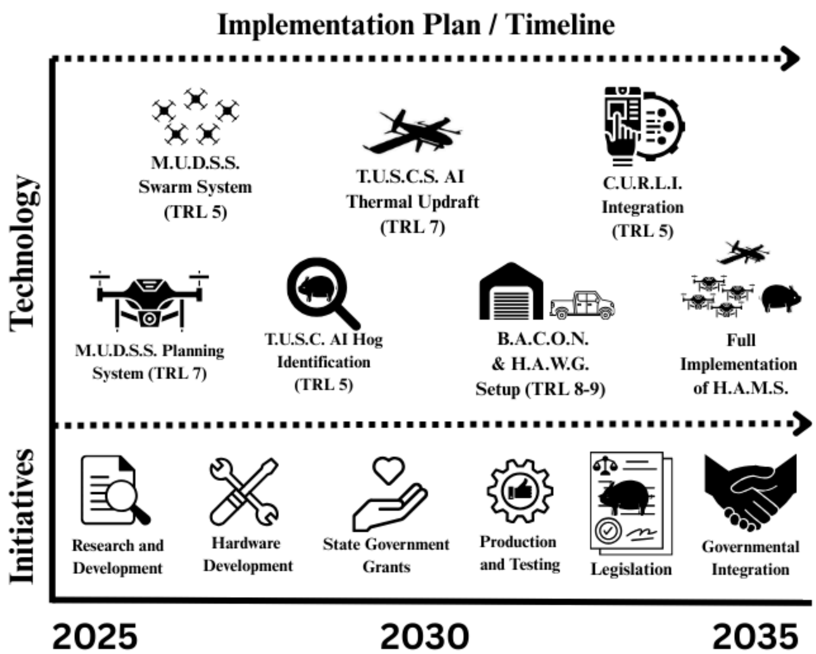


Figure 3.1.1: H.A.M.S. Timeline to Deployment by 2035

3.2 Training

Training for people assisting in H.A.W.G.S. during capture and setup, as well as officials involved in policing illegal hog imports is essential to sustaining the proposed solution. Teams will collaborate with organizations currently in the business of trapping hogs such as USDA APHIS [63], but also with wildlife surveillance teams to better understand the nature of systems in place and how to operate them. However, the autonomous nature of the T.U.S.C. and M.U.D.S.S. reduce training times significantly, abstracting navigation and other processes for the purpose of user friendliness.

3.3 Technology Readiness Level Progression

H.A.M.S. physical systems, such as the sonic deterrents used in M.U.D.S.S. and the T.U.S.C.'s thermal updraft utilization are all technologies with a high TLR [35][64], which can be implemented before 2035. The software systems generally have the lowest TLR. The AI and ML algorithms for identification, object avoidance, and herding swarm used by the M.U.D.S.S. when deployed are less studied use cases of the technology, but even with lower TRL levels, we can still expect these to reach maturity by 2035 as indicated by advances in similar research.

Relative Technology Readiness Level		
Technology	2025-2030	2030-2035
Thermal Updrafts	8-9	9
Sonic Deterrents	8	9
Objective Avoidance	5	9
Hog identification	5	9
Swarm	5	9
C.U.R.L.I.	5	5

3.4 Risk/Barrier Analysis

Due to the already massive amounts of money being poured into the feral hog issue, the most significant barrier to its implementation would be acceptance by the community. For the H.A.M.S. to be widely adopted within the swine management community, it must:

1) *Be more effective than current systems.* H.A.M.S. will increase the effectiveness of past hog mitigation efforts by tackling the areas where those strategies struggle. Current methods used in areas with low hog population density do not have a viable cost of removal per pig due to how spread out they can be. Hogs are also extremely smart and adaptable and may grow used to sounds if they know there is no danger, resulting in alarm strategies failing [11]. Another factor is the harsh terrain that hogs inhabit, making the hogs difficult to reach. Using the interchangeable whistles attached to the M.U.D.S.S., the hogs would not grow accustomed to the sonic devices and would be easily herded out of inaccessible areas and into denser groups, maximizing the cost effectiveness of removal efforts.
2) *Be a turnkey system and easy to train in its use.* The H.A.M.S. would utilize people who already have hog expertise, including hunters, pilots, administrators, and others involved in hog management. Training would need to be provided in the use of the system for the H.A.W.G.S. ground team, including the piloting of drones. To minimize training requirements, systems should be designed easy to use and streamlined. Our team has addressed this by introducing the C.U.R.L.I., an all encompassing software environment used for the control of the various drones in the H.A.M.S. system.
3) *Be robust, yet portable.* The H.A.M.S. targets feral swine that are in areas that make other methods ineffective. These areas include rough terrain and dense vegetation, and so the H.A.M.S. must be able to withstand the conditions found in these wilderness environments. At the same time, since the system is meant to be compatible with the vehicles already used by companies and organizations involved in swine management, the entire system needs to fit within the space provided by these vehicles. These constraints can be addressed by using designs that are dust and water proof and utilize strong lightweight materials, by performing experimentation to optimize the number of M.U.D.S.S. drones and T.U.S.C.s needed, by utilizing connectivity solutions that work in remote areas (such as satellite), and by employing lightweight solar panels and custom fuel tanks to bolster the power generation capabilities built into the vehicle.

4) *Be economically feasible.* Funding for hog management is abundant, with millions of dollars spent each year on research and management activities [3]. To conduct research and develop H.A.M.S. we can seek funding through governmental organizations like USDA APHIS, or through universities with feral hog related research programs such as Texas A&M University. After research and development has been completed, funding for implementing H.A.M.S.s in Texas, which has the highest population of feral hogs in the US, can be achieved through County Feral Hog Abatement Grants. This system encourages Texas counties to make an organized effort to address hog damage and their growing population. Counties may be awarded up to 15 grants ranging from $5,000-$20,000 each, for a total of up to $100,000 [29]. This range provides a feasible starting budget for implementing the system in one county, with many components of a H.A.M.S. being able to service multiple counties. Many nations other than the U.S. deal with the extensive damage inflicted by wild boars. Our long-term goal is to implement the H.A.M.S. internationally, targeting all of Europe, North America, Oceania, Asia, and Central and South America. Funding will come from organizations in individual nations such as the Advancing Pests Animal and Weed Control Solutions Competitive grant from Australia, which has provided $13 million (AUD) to similar projects [30]. Furthermore, we will propose legislation in each country affected by feral swine for the creation of centralized management organizations. While funding is plentiful, to know if H.A.M.S. would provide enough of an economic benefit to be feasible on a large scale would require the construction of an initial prototype and testing to determine its effectiveness.

4. Compelling Key Findings

Table 4.1: H.A.M.S. Key Findings

Finding #	Finding Statement
1	Aviation-based systems, such as the T.U.S.C.s, are capable of identifying and targeting entire feral hog herds simultaneously, surpassing the limitations of traditional trapping methods that only capture partial groups.
2	Current hog removal methods are largely outdated, lacking integration of advanced technologies such as AI and unmanned aerial systems, and are ineffective in reaching hog populations in dense or rugged terrain where the H.A.M.S. system would be able to target those weaknesses.
3	Legislative support for feral hog management is minimal, with weak enforcement against illegal transportation and no centralized infrastructure for coordinated removal efforts; a fully implemented H.A.M.S. would address these gaps through operational efforts and governmental support.
4	Sonic deterrents can be tuned to frequencies that specifically target feral hogs while minimizing disruption to other wildlife. Although drone mounted deterrents have been tested, no system has yet been implemented in active wildlife management, making H.A.M.S. well suited for application in the hog habitat.

5. Expanded Analyses

Since the original proposal, we have updated and framed our system completely. Removing unnecessary parts of the system, adjusting the weight and power balance of our drone aircrafts.

Table 5.1: Changes from Original Proposal

Original Proposal	Addition or Change with Explanation
Aerial eDNA Collection through air from drone	Scrapped idea for it not being researched, complicated, and unnecessary
Compressed Air Whistle Deterrent	An electronic speaker can change frequency, is lighter, and done before on drones
M.U.D.S.S. Deployment from H.A.W.G. Vehicle	Deployment from T.U.S.C.s enables M.U.D.S.S. to reach areas the truck cannot. Limited range
M.U.D.S.S. Quad-copter Design	Hexacopter design can support more payload and is safer if a propeller were to fail, or damage

6. Conclusion

The global feral hog epidemic requires immediate action. They appear to be an unstoppable force that will wreck untold havoc on the world through their ever-expanding numbers and their massive capacity for destruction of crops, livestock, wildlife, ecosystems, and public health. However, humanity's current methodology for feral hog management has key gaps, gaps that can be addressed by our proposed Hog Aerial Mitigation System and through the implementation of effective, common-sense legislation. And with these tools to fight back against hogs, we can take one step closer towards a world without food insecurity, without the fear of zoonotic diseases, without the destruction of landscapes, and without the extinction of Earth's beautiful flora and fauna.

Appendix A: Artificial Intelligence System

AI Trade Studies:

Research into the use case requirements identified computer vision and deep learning as essential technologies. Initially, both machine learning and deep learning were considered for predictive analysis. Deep learning offered superior predictive accuracy but presented challenges in terms of computational power and potential weight, particularly given the use of edge AI devices for on-the-go inference. This on-device inference is crucial for minimizing latency, a critical factor in drone operations, making cloud-based processing unsuitable. To address the computational demands of deep learning on edge devices, the system utilizes a packaged approach with pre-trained models specifically fine-tuned for our application.

Tech Stack:

As detailed in this paper, the AI system's frontend will utilize NVIDIA Jetson AI devices. These were selected for their strong performance at a lower weight compared to standard AI graphics cards, which is crucial for our drone-based application. The software package chosen for on-device inference is the open-source TensorFlow Lite, which integrates seamlessly with the widely adopted and powerful TensorFlow library. For middleware, ROS2 will serve as the primary connection and communication framework. Its lightweight yet robust communication capabilities, commonly used in robotics, make it well-suited for our needs. Finally, Python will be the backend language, directly supporting the use of TensorFlow.

Layer	Technology	Rationale
Frontend	NVIDIA Jetson AI & TensorFlow Lite	High performance and low weight
Middleware	ROS2	Lightweight and Powerful
Backend	Python	Needed for TensorFlow

LSTM Architecture & Pose Estimation

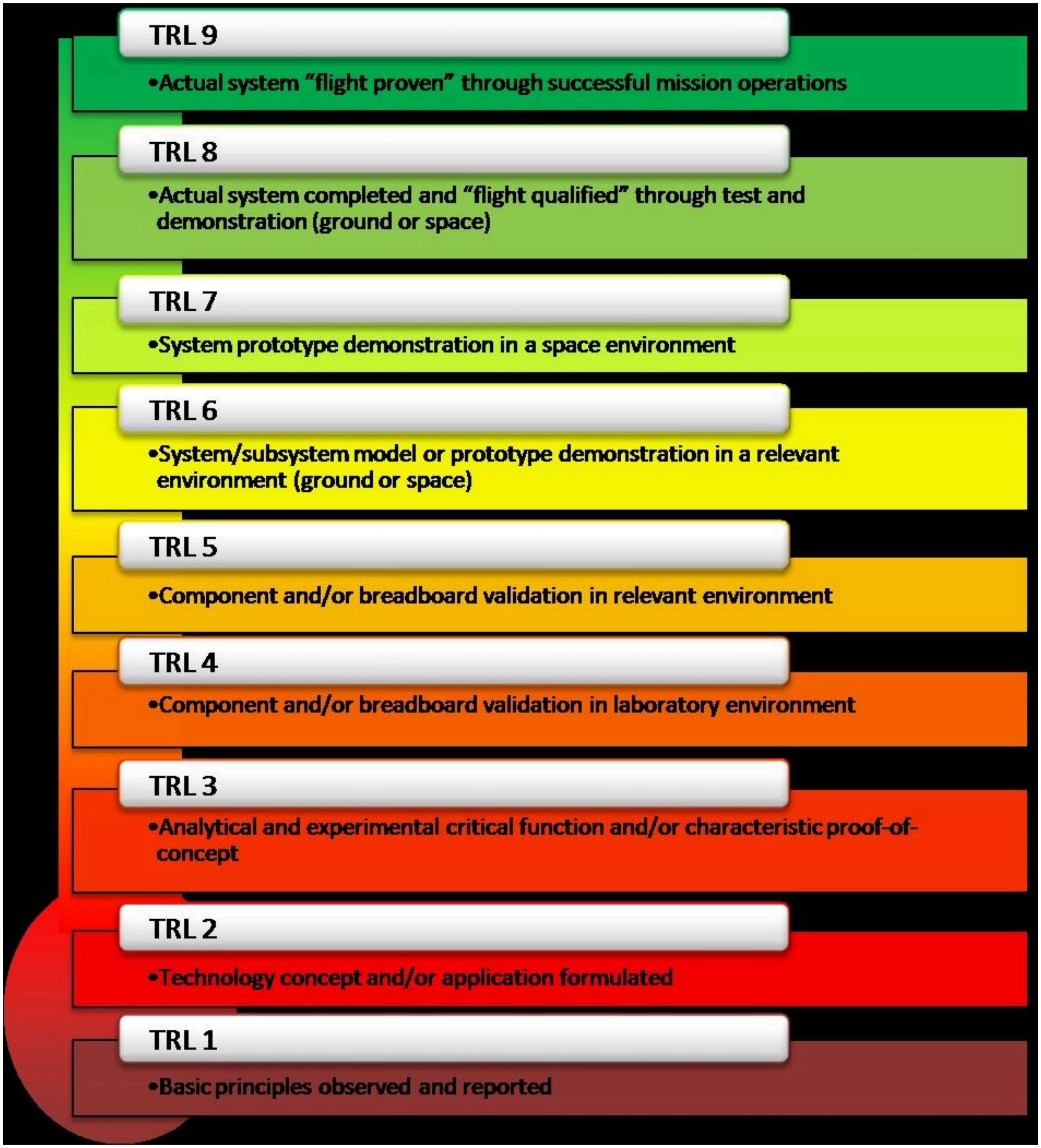
The LSTM [66] architecture employs a three-step gate mechanism that effectively mitigates the vanishing and exploding gradient problems inherent in traditional Recurrent Neural Networks (RNNs). These issues render standard RNNs unpredictable and unsuitable for long-term temporal dependencies, making the LSTM architecture the superior choice for our system's need to analyze behavioral patterns over extended periods.

To process the spatio-temporal GPS data, we will use a concatenation formula: $f(t)=[x(t),y(t),z(t),P(t)]$, where $x(t)$, $y(t)$, and $z(t)$ represent the GPS position at time t, and $P(t)$ is derived from the equation $P(t)=[x1(t),y1(t),x2(t),y2(t),...,xn(t),yn(t)]$, representing the x and y coordinates of n body key points at time t as identified by SLEAP. This concatenated feature vector, f(t), allows the LSTM to learn relationships between both the overall location and the animal's pose over time, crucial for understanding complex behaviors.

The LSTM's hidden state will then be fed into a softmax layer to predict a behavioral label. This layer uses a weight matrix w and a bias vector b, where the output probability of each behavior is given by $softmax(w \cdot h(t)+b)$, with h(t) being the hidden state at time t. The parameters w and b will be learned during training using our labeled wild hog behavior data. This probabilistic output is essential for providing a clear and interpretable prediction of the animal's actions.

Finally, the model's performance will be optimized using the cross-entropy loss function. This standard loss function for multi-class classification will allow the model to effectively learn the distinctions between different behavioral labels, leading to more accurate and reliable predictions of wild hog behavior, which is a core objective of H.A.M.S.

Appendix B: Chart References



B.1 NASA TRL Chart [65]

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