# Embry - Riddle Aeronautical University

### Autonomous Aerial Cattle Monitoring:

# Implementing Low-Stress Aerial Cattle Management on Large Ranches

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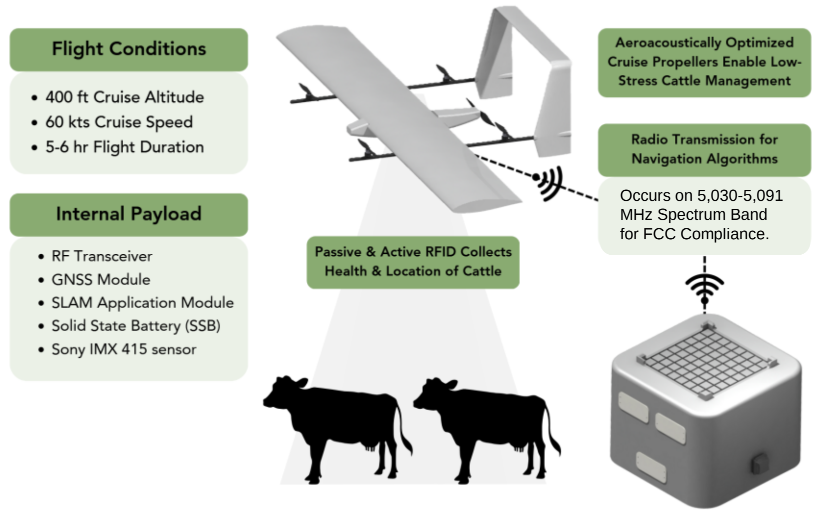
# Contents

# *Sky Shepard: Low-Stress Aerial Cattle Management*

## Project Summary:

The Sky Shepard is a fixed-wing VTOL UAV designed for autonomous cattle health and location monitoring on large scale ranches to address their continuous increasing size since 1970. Current cattle tracking methods are limited in scale and do not consider herd response to stimuli. The Sky Shepard employs low-stress cattle management techniques to ensure herd well-being by using an aeroacoustically optimized propeller to reduce cruise noise. Long flight-times are enabled through the innovative solid-state battery system, and navigation autonomy is achieved with a SLAM model integrated with inertial and global positioning sensors.





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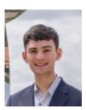
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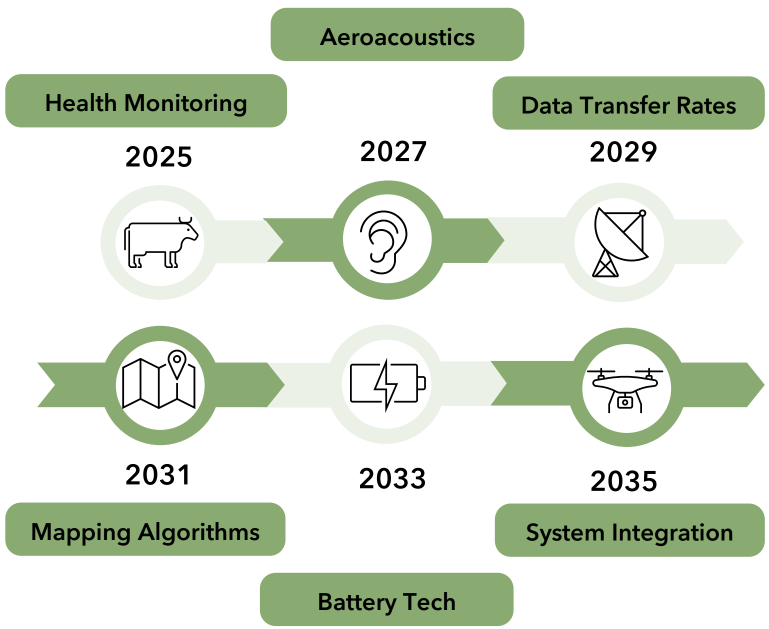
The team's passion for the aerospace field stems from their time at Embry-Riddle Aeronautical University. The team's interest in agricultural sustainability has been reinforced through conversations with ranchers and veterinarians, motivating the concept and design of the final product.



**Abstract**

This paper discusses and proposes innovations and improvements to current methods of large-scale cattle management. Much of modern agriculture can be accomplished with large machinery, however, cattle management is largely done on foot as modern equipment has been found to frighten and cause herd stampeding. Recent technological developments have seen quadcopter Unmanned Aerial Vehicles (UAV) being used in cattle management on smaller ranches, however, quadcopters emit loud noise in a frequency that leads to cattle stress similar to large machinery. Through direct conversations with cattle ranchers and an extensive literature review, research was conducted to determine the feasibility of aeronautical technology on large ranch cattle management. The proposed fixed-wing UAV design concept features an innovative solid-state battery and an aeroacoustically optimized propeller that reduces the sound pressure level and frequency emitted by the UAV to minimize noise that was identified to be irritating for cattle. This concept aims to enhance herd safety and animal welfare by monitoring cattle location and health, allowing for quicker veterinary response times and reduced labor. An implementation timeline was created and areas of future work, including necessary research and testing, were identified.

# 1 Situation Assessment

Low-stress cattle handling and prioritizing cattle well-being in the agriculture industry are increasingly important for ranchers to ensure positive outcomes in animal health, productivity, and safety. Current methods of aerial cattle surveillance, performed using quadcopter UAVs are generally limited to small ranches with under 100 tracking subjects due to the range of the vehicle. The average size of cattle-raising ranches in terms of both acreage and head has increased every year since 1975 [25], as seen in Fig. 1, which drives the need for a higher capacity technology to track and monitor the location of cattle. Using current methods, tracking is particularly difficult on land with limited connectivity where Global Positioning System (GPS) integration and on-foot surveillance are impractical to implement due to the infrastructure and time constraints. On large ranches, aviation is currently utilized to survey herd location on ranches and track down missing cattle; however, this is performed in an expensive manned vehicle with limited precision in communicating position data or how a herd has traveled since last being seen [17]. Implementing a long-range UAV system on large cattle ranches (defined as over 2,000 acres) would reduce the required frequency of existing manual methods and promote animal well-being by providing data on animal location and health.

Current aerial monitoring systems (both manned and unmanned) do not consider the cattle response to the vehicle noise which can induce stress and cause herd movement if it impedes the animal's flight zone. Ranchers are trained to approach cattle using low-stress techniques, which include minimizing noise in order to ensure the safety of themselves and the herd as seen in A.9. Cattle are receptive to frequencies between 27 Hz to 37 kHz with peak sensitivity at frequencies of 8 kHz [8]. Many commercial UAV motors operate between 4,000-11,000 RPM [6] which, depending on number of blades, corresponds to a propeller blade passing frequency in the spectrum of frequencies which cattle are receptive to and higher frequency broadband noise from aerodynamic loadings are prevalent in the 8 kHz range [13] as seen in A.2. Harmful noise has been directly linked to disrupting feed intake, growth, and overall production, as well as affecting reproductive physiology among livestock animals, especially if the noise remains constant. Introducing methods of noise-reduction on aerial cattle surveillance and monitoring systems through the use of aeroacoustically optimized propellers and innovative motor technology on a fixed-wing UAV would mitigate the risks associated with harmful noise and allow ranchers to more easily monitor the health of herds [8].

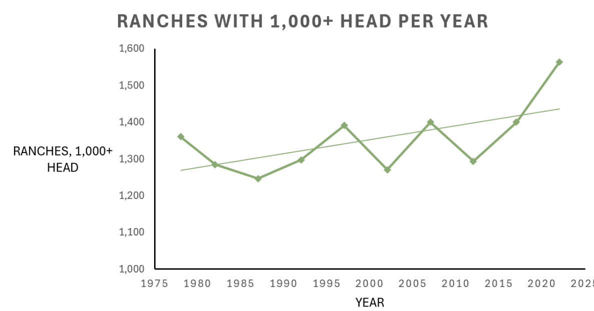



Figure 1: Ranches with 1,000 or more cattle since 1975

# 2 Use Case & Proposed Solution

## 2.1 Use Case Identification

To manage and maintain a herd of cattle, ranchers rely on health, population, and location data to prevent the progression of disease, monitor the inventory and safety of the herd, and to track individuals that tend to wander from the herd. Current methods of herd data collection require ranchers and their hands to ride horses or all terrain vehicles to find the exact location of cattle, and monitor health through visual inspection [17]. On large ranches, monitoring trips can require two to five workers, cover several square miles, and can take most of the day. These methods are costly, imprecise, and inefficient. Furthermore, the data collected are potentially three or more days old, which may lead to delayed identification of disease and other threats.

To aid ranchers and reduce the labor costs associated with these trips, a drone platform is necessary. This drone platform will achieve the following: 1) Reduce labor costs by eliminating the need for ranch hands to physically travel to locate the herd. 2) Use Artificial Intelligence (AI) based mapping algorithms to identify herd location and report herd movements. 3) Monitor herd health in sensitive populations and identify signs of illness using Electronic Collars (E-collars) to optimize treatment response time.

## 2.2 Proposed Solution

In response to the trend of increasing ranch size, a UAV system is proposed to provide location and health data for herds of cattle on large ranches by aerially implementing low-stress cattle management techniques. The target UAV design will be capable of monitoring 6,000 acres and reporting position and health data of up to 2,500 head. The vehicle will possess Vertical Takeoff and Landing capabilities (VTOL), and operate from a central wireless charging pad that serves as the takeoff and landing location and computational center of the system. The cruise propulsion system will feature an aeroacoustically optimized propeller and optimized brushless motor to reduce noise produced by the vehicle by over 10 dB. The aft-mounted cruise propulsion system enables high stability under crosswind conditions experienced during a surveying mission. Extended flight times are supported through innovative solid-state battery technology. In areas with limited to no connectivity, the vehicle will navigate using an AI driven Inertial Navigation System (INS) in conjunction with mapping algorithms to extract position in areas without traditional navigation connectivity. The central base will communicate the mapping algorithms to the onboard flight control system using radio frequency to determine cattle location and health status by interfacing with either E-collars or Radio Frequency Identification (RFID) tags depending on the specific application.

## 2.3 Operation Summary & Code of Federal Regulations (CFR)

For agricultural aircraft operations, UAV systems are regulated under 14 CFR part 137. For autonomous unmanned aerial systems, regulations exist for small UAVs (sUAV) in 14 CFR part 107, and were used to guide the preliminary design of the vehicle. The primary design constraint is an overall weight under 55 lb, which is comprised of the airframe, onboard systems, and payload.

The Sky Shepard will cruise at 60 mph and 400 ft to perform autonomous aerial surveillance flight patterns over ranches. Communication is maintained with the base on the 5GHz spectrum, specifically on the 5,030-5,091 MHz Band in compliance with initial FCC regulations regarding drones [5] from 2024. Beyond Visual Line of Sight (BVLOS) operations require an FAA waiver and will be required to allow for operations on large ranches or ranches with large geographic features. The BVLOS certificate of waiver requires real-time data to be transmitted to the base station and notify the operator of low connectivity or battery, which becomes complicated for autonomous systems due to the volume of data transferred between the drone and base. The device autonomy is expected to extend certification processes and receipt of waivers, moving regulation to the 2030 timeline.

## 2.4 Cost and Return on Investment (ROI)

The development of Sky Shepard began with comprehensive research and development of its core systems, followed by the sourcing and integration of internal and external components. R&D efforts are divided into two phases: software development and physical testing. The software development phase focused on system architecture, SLAM integration, and control algorithms. The testing phase involved real-world validation of key hardware components such as batteries, propulsion, and navigation modules to ensure performance and reliability.

Table 1: Research and Development Cost Analysis

| **Software** | **Estimated Cost** |
|---|---|
| Slam Algorithm Integration | $10,000 |
| GNSS/INS Sensor Fusion | $6,000 |
| Communication Protocol | $5,000 |
| User Interface | $2,000 |
| Total Cost of Software Development | $23,000 |

| Testing | Estimated Cost |
|---|---|
| Wind Tunnel Testing (9 hours) | $9,900 |
| ANSYS Discovery CFD simulations | $5,000 |
| Battery Load | $5,000 |
| Field Testing (Flight Trials) | $3,000 |
| Testing Equipment | $1,000 |
| Total Testing Cost | $23,900 |

Software R&D for Sky Shepard was a significant component of the total development effort. Following OECD Frascati guidelines, these activities qualify as R&D due to the technical uncertainties involved and the creation of novel algorithms and system integrations. Total software-related R&D costs are estimated at $23,000.

The physical testing phase of the Sky Shepard development plays a critical role in validating the UAV's core systems under realistic conditions and ensuring their reliability for field operations. Key components such as the propulsion system, aerodynamic performance, and solid-state battery system undergo testing. Computational Fluid Dynamics simulations using ANSYS Discovery support airflow analysis around the UAV body and propeller. Wind tunnel testing, totaling nine hours, assesses aeroacoustic behavior and informs propeller optimization for low-stress cattle interaction. The team conducts field flight trials to confirm autonomous stability, navigation accuracy, and hardware integration in open-range environments. This combination of lab-based and in-field testing provides critical insights into system performance and helps refine design parameters ahead of deployment. The total cost of physical lab and field testing for Sky Shepard is $23,900. [1] [3] [20]

The return on investment for individual ranchers utilizing Sky Shepard varies depending on several factors, including herd size and the chosen monitoring system. Costs for the UAV differ case by case, influenced by the scale of deployment and specific hardware selections. A detailed breakdown of pricing for the Sky Shepard system and its support components is provided in Table 2.

Table 2: Sky Shepard Platform Cost

| Internal Systems | Cost |
|---|---|
| 4 Brushless 2,020Kv Motors (VTOL motors) | $180.00 |
| 1 Brushless 1,750Kv Motor (main power motor) | $43.00 |
| Solid-State Battery | $720.18 |
| RF Transceiver and Antenna | $70.00 |
| GNSS module | $650.00 |
| SONY IMX 415 Camera Sensor | $69.99 |
| SLAM Application Module | $250.00 |
| Total Cost | $1,983.17 |

| Support Systems | Cost |
|---|---|
| CowTraq Neck Collars | $48,000.00 |
| Electronic Ear Tags | $1,000.00 |
| Landing Pad Computer System | $1,250.00 |
| Skycharge Conductive Charger | $6,386.25 |
| Internal Electronics of Landing Pad | $180.00 |
| 2 Landing Pad Batteries | $3,143.50 |
| Total Cost | $59,959.75 |

The total cost of Sky Shepard for a 400-head herd is $61,942.92. Sky Shepard eliminates the need for two trips per week, by A.1, saving ranchers approximately $1,200 weekly. At that rate, ranchers would recover the system's initial cost in roughly one year, resulting in an annual ROI of about 100 percent after the first year.

# 3 Technical Development and Implementation

## 3.1 Propulsion System Acoustics

Modern propeller design seeks to balance performance gains with acoustic penalties. The proposed solution will implement innovative propeller geometry for the cruise segment of the mission, which requires low propeller noise over the region of interest to comply with low-stress cattle management techniques. Gaps in existing research exist for optimizing UAV propellers for fixed-wing systems where turbulent inflow is present, with many existing sources assuming steady flow for cruise conditions or ignoring the effect of wing and fuselage interactions.

Propeller Sound Pressure Level (SPL) optimizations have been performed using simulations, and are currently capable of reducing noise by 5 dB without compromising on propeller efficiency or performance [29]. SPL reductions were done by reducing the local airfoil angle of attack on the inner span-wise portion of the blade and increasing the chord-wise length between the 60% and 80% span-wise radii, as seen graphically in A.3. Modifying both geometries allowed performance to stay balanced with acoustic reductions [29]. Similar chord length modifications were performed experimentally in 2013 where maximum SPL reductions of 12 dB were found as seen in A.4, including lowering noise levels at 8 kHz [22]. Additionally, SPL optimizations can be made by reducing the rotational speed of the propeller, in turn lowering the Blade Passing Frequency (BPF) and broadband noise. This is most easily done by increasing the span of the propeller, which is geometrically constrained by the placement on the UAV, however, the larger diameter also enables efficiency gains.

Challenges arise when considering the propeller inflow conditions, particularly for a pusher-style propulsion system which must consider the fuselage and wing interaction with the propeller. Much of existing research in propeller aeroacoustic optimization in the scale of UAVs has assumed steady inflow due to the computational cost of LES (Large Eddy Simulation) required for fidelity in acoustic results, however, analysis of existing propeller geometry with turbulent inflow has been explored. It was found that higher inflow velocity and turbulence models increased the noise for comparable propellers up to 15 dB, particularly above 1 kHz [12]. This can be seen by comparing the cases in the Overall Sound Pressure Level (OASPL) as a function of microphone location in Fig. 2. In addition to turbulent flows, the effect of noise from viscous contributions in the propeller inflow has been experimentally demonstrated to increase the broadband contribution in the mid-range frequencies (300 Hz - 10 kHz) [30].

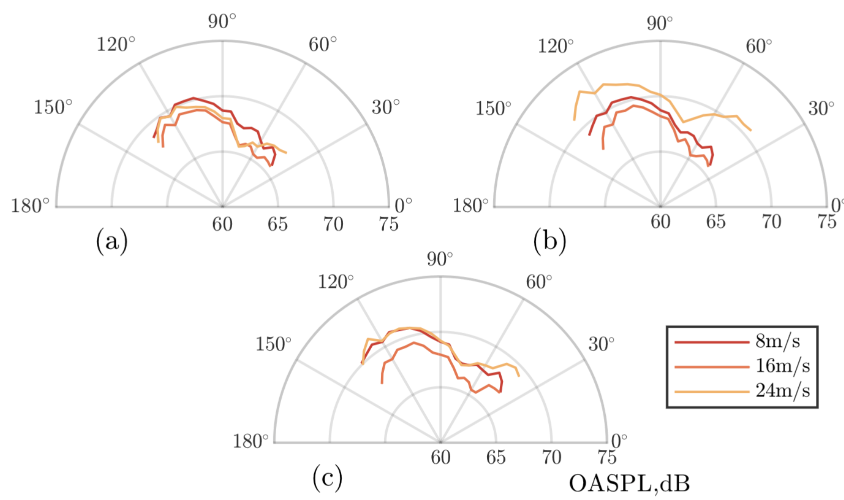



Figure 2: Effect of Inflow Velocity on OASPL for Laminar (a), Grid Turbulence (b), and Wing Wake (c) Inflow. [12]

Modeling the effect of aeroacoustically optimized propeller geometries in the discussed viscous or turbulent inflow cases has not been performed on the scale of small fixed-wing UAVs. Similar experimental design setups can be used to match flight conditions experienced by the Sky Shepard. It is proposed that turbulent and viscous effects are experimentally tested to investigate the effect of the discussed noise-reducing geometries with particular attention to how broadband noise in the frequency which cattle are most receptive to is reduced.

The technology exists to design and test updated blade geometry at cruise conditions to investigate a reduction in SPL. The existing cited research has validated results over the past ten years both analytically and experimentally and provides a baseline for rig setup. Investigating new combined geometries under various inflow conditions can be performed at a Technology Readiness Level (TRL) of 5, and are likely able to be researched and implemented by 2027. Unsteady CFD (Computational Fluid Dynamics) simulations have been used to validate fan geometry [24], however, were performed at much higher Reynolds and Mach numbers requiring scaling to determine applicability to UAV propellers. Experimental validation in anechoic Wind Tunnels as seen in A.5 are commonly used in aeroacoustic testing and are capable of operation in flow regimes required to pursue testing of UAV propellers. The state-of-the-art facility summarized in A.5 is capable of eliminating acoustic reflections above 140 Hz, which would provide fidelity in testing the results of propeller geometry in the mid-frequency range. The proposed innovations will reduce the SPL in the mid-frequency ranges which cattle are most receptive to allowing for reduced stress in cattle management.

Further reduction in SPL is achieved by the distance attenuation of the propeller noise. To test the effect of distance on SPL for the turbulent inflow case tested in [12], calculations summarized in A.8 were used to compare the SPL as a function of the distance from the source, as seen in Fig. 3. The distance attenuation will further reduce the propeller noise herd by the cattle.

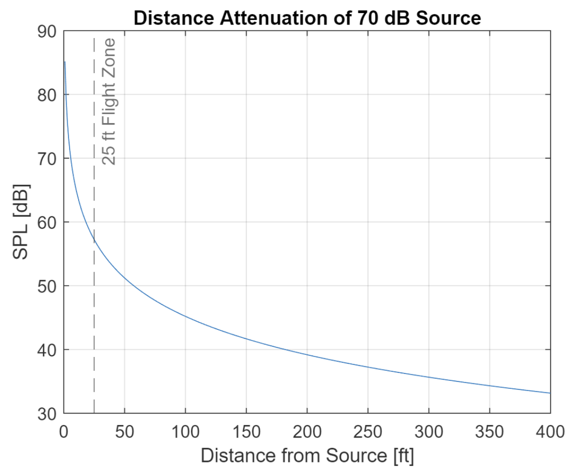



Figure 3: Distance Attenuation of Propeller Source

Several other experimental or developmental propulsion technologies were considered in the design process, including ducted fans and bio-mimetic propellers with leading-edge serrations. It was determined that while ducted fans would provide enhanced tonal noise reduction [9], the added weight of the duct would introduce performance losses that would not outweigh the aeroacoustic benefits. Alternatively, bio-mimicry designs, such as leading-edge serrations to mimic owl wings, have shown acoustic reduction while also increasing thrust forces. By analyzing sawtooth propeller designs in Computational Fluid Dynamics (CFD) simulations, the design was shown to reduce noise by approximately 4.18 dB, and increase thrust by 3.53% [28]. Although research on bio-mimetic designs is still limited, these designs prove to be more efficient for acoustic reduction and flight performance compared to ducted fans or common propeller shapes utilized at present.

## 3.2 Flight Zone

Flight Zone is the area around an animal that, if entered, will cause the animal to move. Moving towards the cow can cause the animal to move forward, and moving away from the cow can make it stop moving. On a two-dimensional sense, approaching the cow from a specific area will cause the cow to move away in that direction [11]. Utilizing low-stress, behaviorally informed cattle management by foot improves cattle well-being and handler safety; however, it has primarily been studied in 2-D as seen in A.9. Adding the third dimension is necessary to understand the effects of drone noise on cattle, and research at Sam Houston State University analyzed the reactions as a standard quadcopter lowered closer to the animal. The study concluded a minimum safe altitude of 25 ft before the cattle reacted to the drone as seen in A.9. To ensure low-stress cattle management, the minimum height of the UAV when operating over animals was selected to be 25 ft [14], noting that the typical cruise height of 400 ft for the UAV is significantly higher than the flight zone boundary.

## 3.3 Navigation and Autonomy

A multi-sensor Simultaneous Localization and Mapping (SLAM) model can be implemented to track the location of the vehicle while performing mapping tasks along the mission. Utilizing the implemented sensors for monitoring cattle and adding sensors with complementary strengths, for example camera, Inertial Measurement Units (IMU), and Global Navigation Satellite Systems (GNSS), accurate position data can be transmitted to track cattle location.

### 3.3.1 Simultaneous Localization and Mapping (SLAM)

SLAM utilizes a sequential movement estimation algorithm to stitch together sensor data, from which the position is extracted. Sensors can include radar, LiDAR, or cameras with integrated AI imaging models. The AI driven camera system proposed for the Sky Shepard utilizes a Sony IMX 415 camera sensor due to its light weight and low-cost relative to radar and LiDAR.

For longer-duration missions, estimation error can become large. To minimize error, introducing navigation boundaries would limit the possible solutions of the algorithm leading to higher computational efficiency and minimizing extraneous solutions. The proposed system would allow ranchers to manually define the borders of their property or input parcel data which would retrieve Geographic Information System (GIS) data. These navigation boundary conditions would be converted to a Pose Graph, which is particularly effective for far-from-base tracking as the defined boundaries provide additional data for the algorithm to process when communication with the base is limited.

### 3.3.2 Inertial Navigation Systems (INS) and Global Navigation Satellite Systems (GNSS)

A challenge with the use of UAV systems comes with geographic positioning. There are several different approaches to solving this challenge. One solution is GNSS, and another is INS. These systems use Real-Time Kinematic Positioning (RTK) by collecting data from comparing two antennas, one located at the UAV base and charging system, and another located on the UAV.

### 3.3.3 SLAM and GNSS Integration

Integrating GNSS with the SLAM algorithm allows for accurate positioning in a range of environments, including outdoor windy environments. Integration of GNSS and INS can be achieved using different levels of coupling ranging from loosely coupled to tightly coupled, each with associated algorithm modifications. The coupled integration system is proposed for the Sky Shepard as it is the most suitable for outdoor areas with limited satellite visibility. The coupled integration system uses a Kalman filter to measure error within the system through the INS and GNSS data collection system, as seen in A.7, to provide measurements of the pseudorange, carrier phase, or Doppler shift [7]. By integrating GNSS and SLAM, the result provides an extremely useful tool for mapping and positioning in areas with and without satellite connectivity. GNSS and SLAM integration technology has a TRL of 5 due to the innovative integration, and is expected to be capable of implementation by 2030 as further integration experimentation is required before the system can be successfully implemented. [21].

## 3.4 Animal-UAV Connectivity

Animal identification allows ranchers to track health history, lost animals, buying & selling, and many other factors. Currently, the most common form of identification is standard ear tagging. With standard ear tagging, a unique number is assigned to each animal and respective data must be collected manually [18]. Current methods make it difficult for large-scale ranches to comprehensively understand their herds' health other than by performing a visual inspection.

E-collars, most commonly used in dairy farming, are placed around the neck of the cattle. These collars track data such as signs of heat, rumination and early detection of health issues. The data collected from the collars are automatically stored in a retrievable database [26]. Current examples of cow collars generally use radio frequency to transmit all of this data to a 'home base' antenna and can communicate to distances of approximately 75 meters. For applications in the Sky Shepard, the collars would be best suited to be placed on breeding females. This is because many farms only run their bulls with females when they are in heat. Using the collar in conjunction with the Sky Shepard would allow farmers to make more informed decisions about the health and breeding statistics of their herds. As the drone flies over head at its selected 400 feet flight height, an antenna placed on the drone will be able to scan and send all collected information back to the UAV's base.

Even with new technologies, all cattle must also be fit with a form of identification ear tags. Depending on their budget, ranchers are able to decide between standard or RFID-equipped ear tags. Standard ear tags are the simplest option, however, they have no way of communicating with the drone. Electronic ear tags that implement long-range RFID technology can be used. Similarly to standard tags, they provide identification data, but RFID tags can communicate with drones passing overhead using the same technology as E-collars[18]. In essence, users can decide which ear tags they prefer and how many RFID-equipped ear tags they would like to use based on budget and how they would like to apply the technology to better serve their herd.

The proposed solution implements an RFID receiver on the drone which communicates with the RFID ear tags or collars by receiving and transmitting radio waves. The pairing of RFID collars and tags with the UAV automates the time-consuming process of continuously checking grazing cattle and provides information to improve overall herd health. The options and uses for each type of tracking hardware are summarized in Fig. 4

Current passive RFID technologies have not expanded to long-range capabilities for electronic ear tags. E-collars can transmit live information between 75 and 250 meters away, which is in the drone's flight range. [26] The RFID system of the proposed drone is assigned a TRL of 6 due to the development needed to increase passive RFID data transmission range. Because of this, the system would be feasible in the next several years [27].

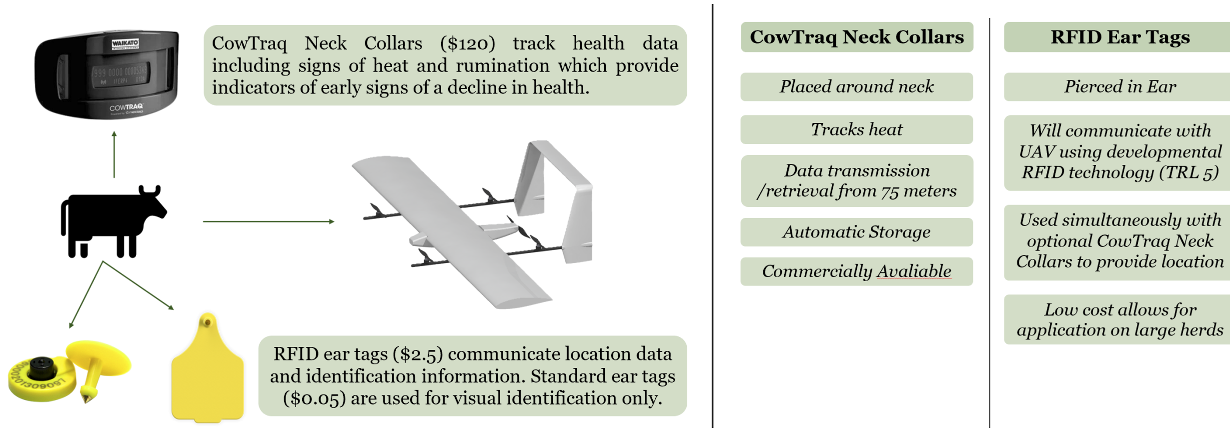



Figure 4: Comparing Collar Options and Applications

### 3.5 UAV Support System

The UAV Support System allows the UAV to perform continuously and autonomously. This system is comprised of three layers. Layer one is made of backup batteries if power is lost. Two batteries [15] sustain the navigation system and wireless charging for an extended period so the UAV can continue monitoring bovine movement and observe dangerous health events. Layer two is for computing. Rather than requiring the UAV to calculate the flight path and process the bovine movement data internally, the base computer communicates with the UAV to enable the higher processing power that is required to sustain the navigation/positioning algorithm. Layer three is the top layer, where the UAV lands and charges. Upon approach, this layer uses external hardware [23] to orient the UAV on the landing pad for inductive charging. As all components of the UAV Support Module are commercially available, this module has a TRL of 9.

RF is the commanding tool in UAV communication with the Support System and is used to communicate the cattle location and health information to the rancher. The UAV acts as a relay, with the drone receiving the RFID data from the herd and transmitting cattle health and the current UAV position to the base. The data transfer occurs on the 5,030-5,091 MHz spectrum band [5]. Due to the high volume of data transfer required to run the integrated SLAM algorithm, advancements in radio transmission would need to be made before implementation. At a TRL of 5, this would need to be done before 2029, before the integration of the SLAM algorithm.

### 3.6 Battery Innovations

The energy density and cycle behavior of batteries are essential parameters in the design of a UAV and serve as areas for innovation. Solid-State Batteries (SSBs) have been identified as a battery technology that utilizes a solid electrolyte composition for ionic conduction between the electrodes. Li-ion SSBs have many advantages over traditional Li-ion batteries: higher energy density, faster charging, longer life, and even increased safety. Additionally, the cost of SSBs is comparable to traditional Li-ion batteries, as seen in A.6. SSB's energy density research has yielded promising results in the form of lithium superionic conductor (LISICON). When paired with the proper formula, LISICON material SSBs provided an energy density capacity exceeding 2500W $kg^{-1}$ at a current density of 5016m $Ag^{-1}$, proving LISICON's importance in the future of SSBs. Utilizing SSBs in the UAV allows for a longer flight time, increased payload capabilities, and increased reliability. The TRL for Li-ion SSBs is 4 due to the need for extensive further research and innovation before implementation [19]. Based on the research and development needed, implementation by 2035 is expected.

# 4 Path to Deployment

Fig. 5 summarizes the critical milestones required for full deployment in 2035. First, development in passive RFID technology outlined in 3.4 is completed by 2026 to enable the UAV to identify ear tags. Experimental validation in aeroacoustics research outlined in 3.1 will be complete by 2027. By 2029, data transfer rates on the 5030-5091 MHz spectrum band will be able to support the SLAM algorithm outlined in 3.3.3 in compliance with FCC and FAA CFR regulations. By 2031, the SLAM algorithm is fully developed, and compliance with evolving CFR regulations surrounding autonomous UAV technology is certified. By 2033, the Solid-State Battery technology outlined in 3.6 will support the proposed mission. By 2035, integration will be performed on the systems discussed in the proposal, and assembly will be complete. Discussions with veterinarians [16] identified a practical use-case for the device and emphasized the importance of noise reduction. Additionally, discussions with ranchers utilizing existing cattle management strategies on large ranches [17] showed express interest in the technology citing time and labor improvements.

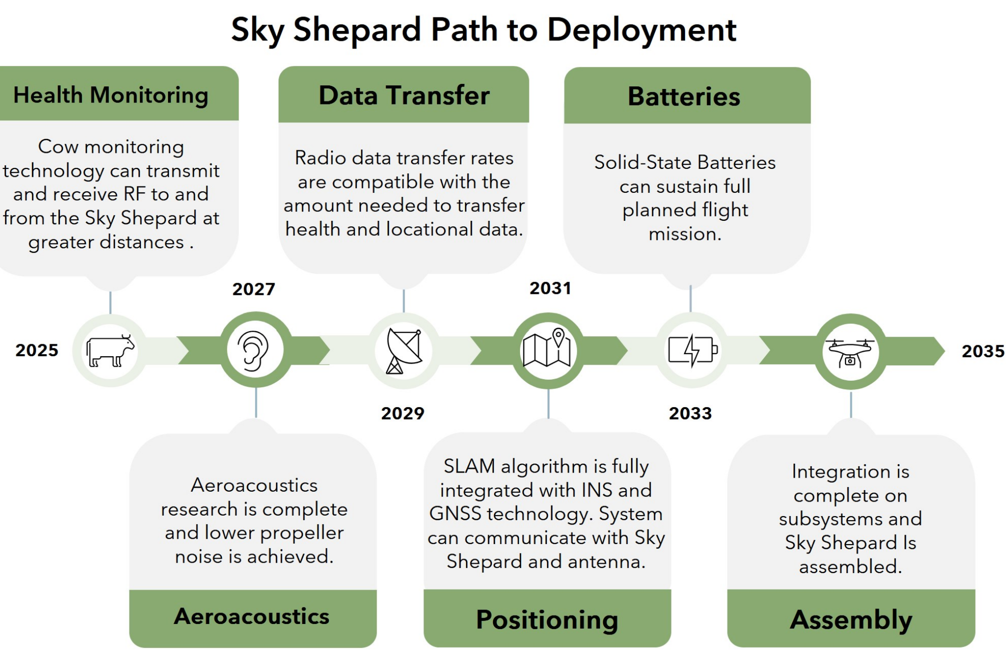



Figure 5: Sky Shepard Implementation Timeline

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# A Appendix

## A.1 Labor Calculation

Five workers receiving $20 an hour for two six-hour trips a week equals $1,200 being paid to the workers.
ROI=(yearly savings/ initial investment)*100
ROI=($1,200*52/$61,943)*100=100.6%

## A.2 Quadcopter Frequency Spectrum

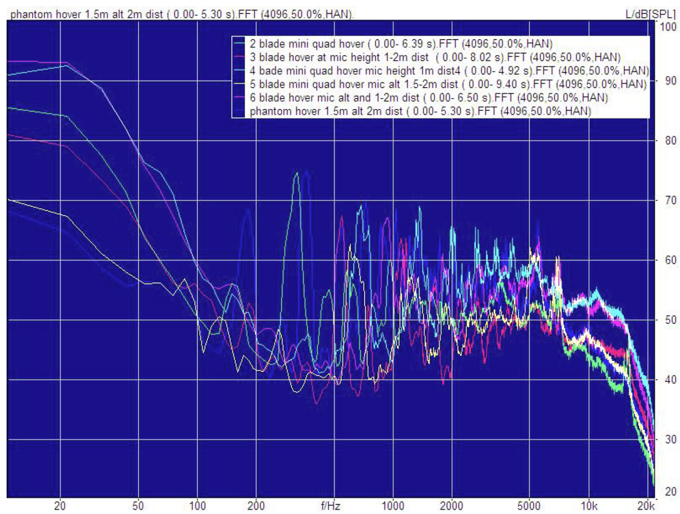


Figure 6: Frequency Spectrum for Various Quadcopter Configurations [13]

## A.3 Chord Distribution

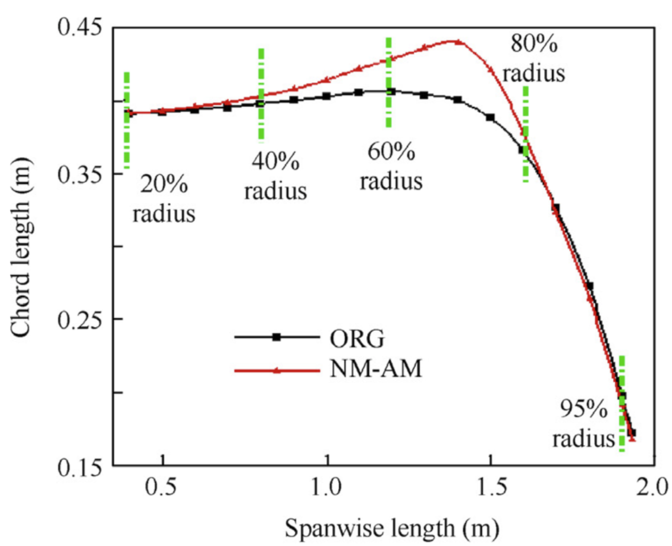


Figure 7: Chord Distribution as Function of Span [12]

## A.4 Chordwise Distribution

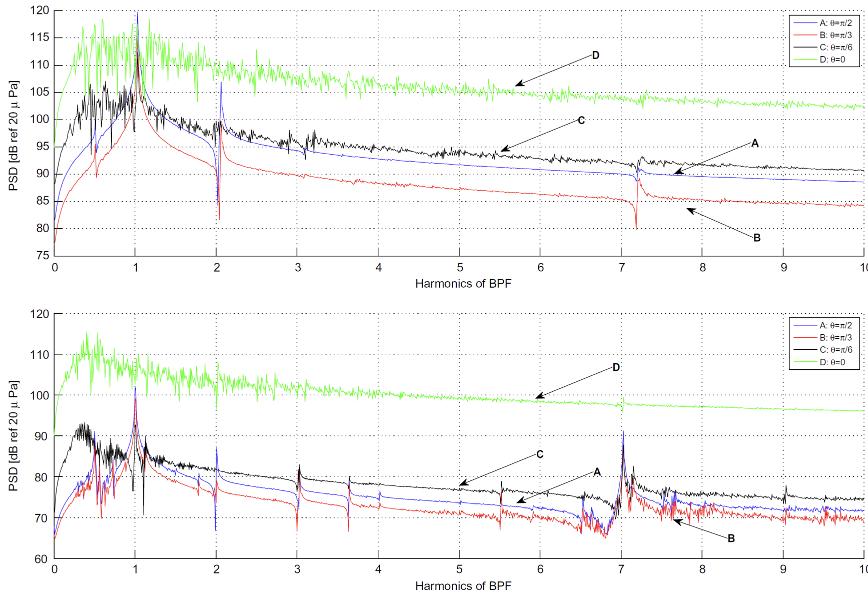


Figure 8: Comparison of Harmonics for Conventional (top) and Modified (bottom) Propeller Geometries [22]

## A.5 Anechoic Wind Tunnel Schematic

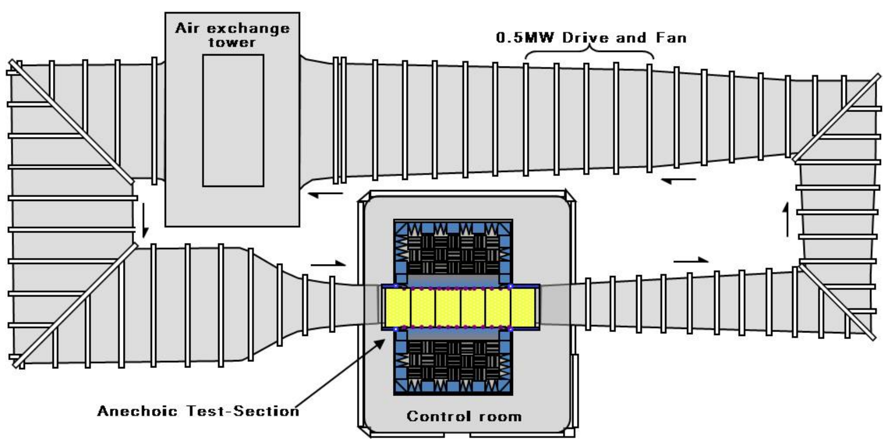


Figure 9: Schematic of Wind Tunnel with Anechoic Test Section for Aeroacoustic Research [10]

## A.6 Solid State Battery Cost Comparison

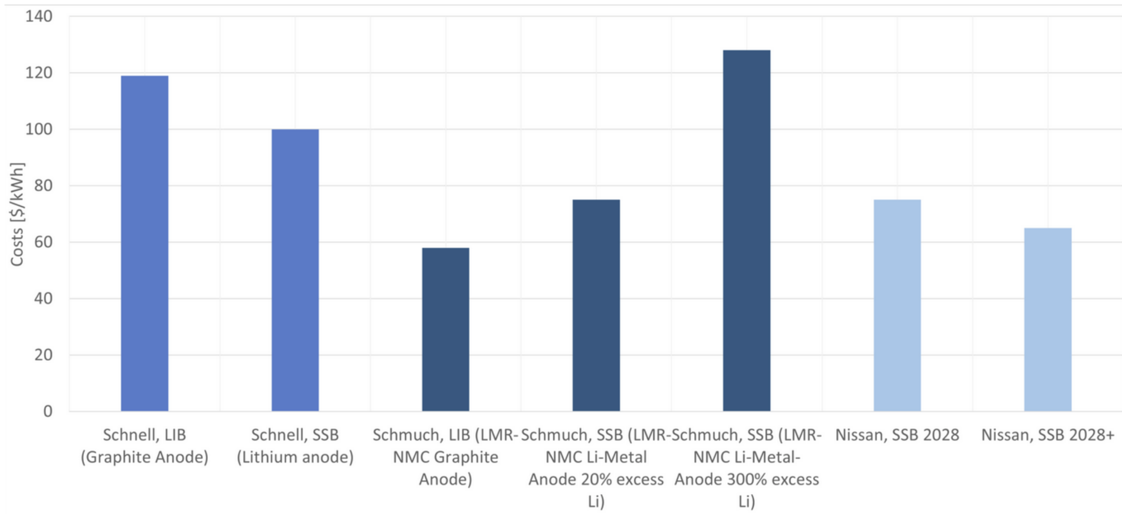


Figure 10: Solid State vs Li-ion Battery Price Comparison [4]

## A.7 GNSS/INS SLAM Integration Method

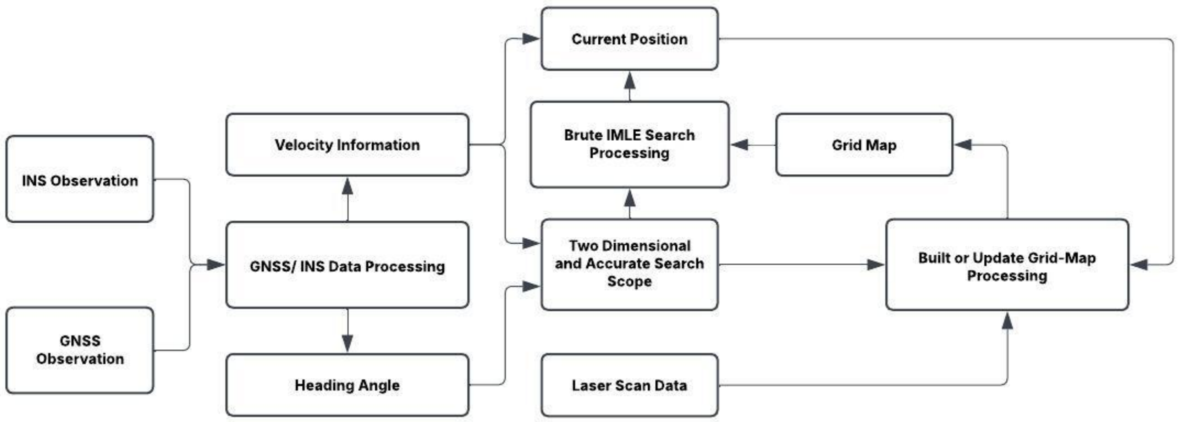


Figure 11: Diagram of GNSS/INS SLAM Integration Method

## A.8 Distance Attenuation

Sound Attenuation was calculated using:

$$SPL_2 = SPL_1 - 20\log_{10}\left[\frac{R_2}{R_1}\right] \tag{1}$$

To create the distance attenuation plot, experimental results from the turbulent test at 24 m/s measured at $90^o$ [12] were used. A source SPL of 70 dB at 1.75m (5.75 ft) was asssumed, and the distance $R_2$ was left variable to explore the effects of moving away from the propeller.

## A.9 2-D vs 3-D Cattle Flight Zone

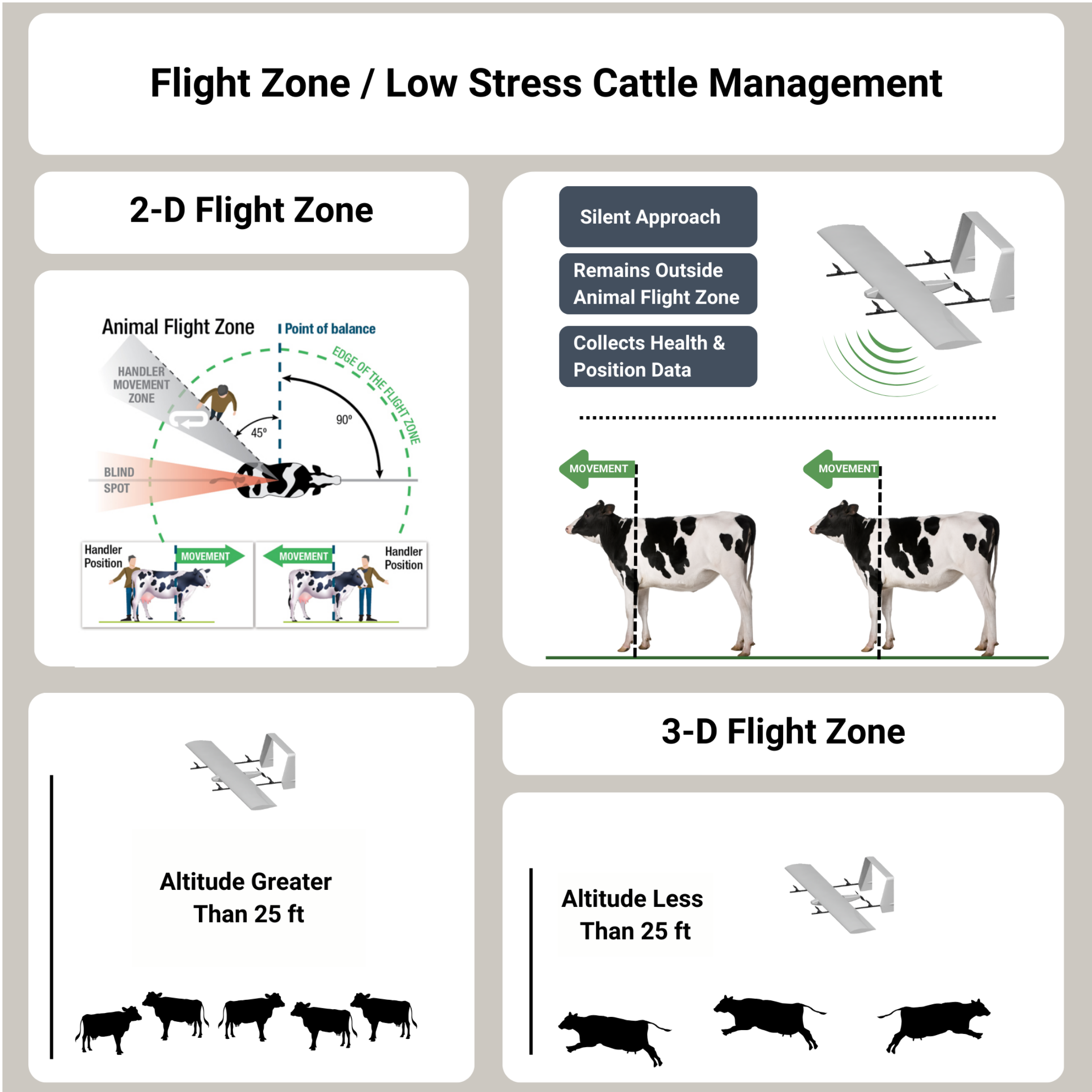


Figure 12: (Team Developed) Low-Stress Cattle Management Techniques applied to Aerial Surveillance. [2] [11]