AREND: A sensor aircraft to support wildlife rangers

J. N. Koster¹ and A. Buysse²

University of Colorado, Boulder, CO 80309-0429, USA

L. Smith³ and R. J. Huyssen⁴

University of Pretoria, Pretoria, South Africa

J. Schneider⁵

University of Stuttgart, Stuttgart, Germany

J. Hotchkiss⁶ and J. Malangoni⁷

Metropolia University, Helsinki, Finland

An international student team AREND (Aircraft for Rhino and ENvironmental Defense) is collaborating to design, build and fly an electric unmanned aerial system (UAS) in support of anti-poaching operations conducted by rangers in South Africa. The solution shall constitute, but not be limited to, an unmanned fixed-wing aircraft capable of conducting remote surveillance of large park areas with diverse intelligence gathering sensors, along with a network of ground sensors. The primary challenge in the poaching problem is to develop a proactive technological solution to prevent the poachers and rhinos from ever meeting. Multiple requirements and challenges are derived from this strategy in order to develop a comprehensive design. The AREND electric aircraft system is capable of quickly delivering selected payloads to any location within a 30 km radius, silently performing a search pattern, returning to a landing area and landing safely within the park or reserve. The aircraft system has been designed from ground up around selected sensor requirements. The aircraft structure and volume are designed to accept a variety of payload modules and particularly sized to support the largest expected payload. It is made of advanced composite materials and has a highly efficient aerodynamic shape to remain airborne for at least 90 minutes. The standard payload includes a gimbal-stabilized visual camera system, capable of capturing high-resolution image data throughout the search pattern of the flight mission. Visual cameras help with surveillance of the area for poachers and rhinos during the day. The GPS location data informs the rangers about the exact location of observed rhinos and poachers so they can pursue and intercept an encounter between them. A ground sensor network capable of gathering data relevant to the anti-poaching effort and remotely transmitting data to other ground systems, air systems and a central command center is included. Several subsystems have been tested individually and integrated into the prototype airframe which successfully passed initial structural and flight mechanical testing. Making use of the different Universities complimentary technical skills, subsystems were divided amongst the students internationally and weekly meetings ensure alignment between designs. Independent global team organization requires a global project manager with excellent personal skills and understanding of the system engineering process to develop a successful collaborative work environment. Experience gained by students was not limited to systems engineering design of a small aircraft, but also provided an opportunity for the students to learn skills in global research and development collaboration, which is of interest to global technology corporations.

¹ Jean N Koster, Professor Emeritus, University of Colorado, Boulder, CO 80309-0429, USA
² Aaron Buysse, Graduate Student, University of Colorado, Boulder, CO 80309-0429, USA
³ Lelanie Smith, University of Pretoria, South Africa
⁴ Joachim Huyssen, University of Pretoria, South Africa
⁵ Johannes Schneider, University of Stuttgart, Germany
⁶ Joseph Hotchkiss, Metropolia University of Applied Science, Helsinki, Finland
⁷ Jonathan Malangoni, Metropolia University of Applied Science, Helsinki, Finland
I. Introduction

The primary challenge in the poaching problem is to find rhino poachers before they can commit the killings. At the core of this project the concept of operations and requirements are designed to prevent the poachers and rhinos from ever meeting. This stands in contrast to the typical alternative objective of merely offering a combat advantage to the park ranger teams that are engaging the poachers.

A strategy to attempt to find the poachers is developed resulting from the decision to design a proactive technological solution to prevent rhino poaching. The proactive strategy is considerably more difficult than a reactive one because of the large size of the Kruger National Park, the dense vegetation, the limitation of data transmission and the limitation of human investigation of remotely sensed data. These potential difficulties motivate the need for a high range and high endurance aircraft, as well as a park-wide ground sensor network.

Furthermore, the AREND team recognizes that the poaching industry is extremely well funded and very profitable and thus poachers will adapt their methods in response to strategies against them. In order to maintain an unmanned aerial system (UAS) that can remain more advanced than the poachers and accommodate the rapid advancement of sensor technology, the design must allow for modular implementation of new sensor technology within the airframe and embedded system.

The core challenges in this development project are therefore to develop:

- an aircraft capable of immediate, fast and far delivery of a payload for long distance, silent flight in the search sector,
- a payload with high resolution stabilized sensors together with a sophisticated onboard image processing facility,
- an aircraft capable of interfacing with a variety of payload sensors and allow for modular payload implementation,
- a ground sensor network capable of detecting movement within the search sector and relaying collected data to the aircraft and park rangers for further investigation.

A. Top Level System Requirements

The top level requirements of this UAS were derived from the following operational challenges. The size of the desired surveillance area of the Kruger National Park drives the design decision for a sector aircraft to patrol large areas of a park for an extended duration and permit a quick response to a poaching threat. The defined search radius of about 30 km places constraints on the amount of data transmitted to the ground and motivates the need for on-board processing of the sensor data. The embedded system needs to be designed to process high resolution images on-board, which reserves bandwidth for the downlink of telemetry data and select images or sensor data for expert human verification of a poaching threat.

Since it is easy to hide in the South African bush, the aircraft must remain undetected by poachers. Thus the aircraft is designed to fly at a high altitude and generate as little noise as possible. The altitude is constrained to 120 m above ground level (AGL) by government regulations. The requirements driving camera and sensor specifications are then derived from the search altitude. The airframe itself is designed around the mass and volume requirements of expected sensors and embedded system components, as well as the requirements for search speed and endurance.

In summary, the aircraft must perform a search pattern in a large sector of the park with payload sensors designed to autonomously detect humans and rhinos. The UAS must allow for human confirmation of a possible poaching threat and continue to observe the threat (loiter) while park rangers respond. Furthermore, the audio horizon of the aircraft, or the distance at which the noise generated by the aircraft is indistinguishable from ambient
noise, must be sufficiently above ground level to remain undetected by poachers. To achieve these objectives, the aircraft shall be an unmanned fixed-wing aircraft equipped with intelligence gathering sensors, be constructed of advanced composite materials and be designed to be aerodynamically efficient. Figure 1 illustrates the flight mission for the UAS previously described.

![Figure 1: Description of the search segment and mission design.](image1)

The basic design of the aircraft is shown in Fig. 2. The nose of the fuselage shall include a camera gimbal and the rest of the fuselage houses the power system, embedded system and modular sensor payloads. The data from these sensors shall be tagged with GPS location data and used to inform the rangers about the exact location of rhinos and poachers so they can pursue on the ground. Team AREND is exploring select intelligence gathering methods as well to create an efficient aircraft system to detect and catch poachers during operations, during both day and night.

![Figure 2: AREND aircraft concept.](image2)

II. Aircraft and Aircraft Subsystem Design
Leading from the strategy and flight objectives the aircraft design phase of configuration design and preliminary sizing follows. The primary performance objective for the aircraft is maximum range and during observation loiter, when poachers have been spotted, maximum endurance. Then the primary operational objectives (payload mass, flight speed, air density) can be selected. The main drivers for the all-up mass are the payload mass and range requirements. Since all-up mass detail requirements was not available at this phase the all-up mass was set at a maximum limit of 20kg to adhere to UAS class regulations, with a given estimate of 3kg for the payload mass. The intended operational location (Kruger National Park (KNP), South Africa) situated at 400m ASL has high temperatures leading to higher density altitude. This together with the regulation of 120m for civil UAS systems as maximum flying altitude left the density estimate at 1 to 1.2 kg/m³.

The design airspeed was a product of the time allowed to reach the area of interest, time allowed to search within the area of interest, the size of the area of interest as well as wind and turbulence conditions in the KNP. Additional requirements were that flight must be silent and an upper limit to the flight speed is dictated by the payload sensor system (sensor resolution, target resolution, frame rate and search frame size) to process observations of sufficient quality. The principle flight section will be the observation section leading to a design airspeed of 20m/s with a search sector of 60km diameter.

A. Airfoil Selection and Wing Design

Based on the design cruise speed of 20 m/s and the initial expected wing chord length of 0.2 m – 0.5 m the Reynolds number Re is calculated to be between 260,000 – 660,000. Several low Re airfoils were selected and analyzed using XFOIL in order to estimate the ideal airfoil (best lift to lowest drag) selection for the Re range. The selection of the airfoil also considered in terms of ease of manufacturing (thicker airfoil) compared to potential stall trade-offs (thicker airfoil at low Re increases drag as thickness increases). The set of airfoils included the E193, SD7062, SA7038, FX-38-W108 and the E214 airfoils. The E214, which is a low Re airfoil, was selected for the AREND UAS based on the lift requirements for the 18 kg with the lowest drag. The E214 has a camber of 4% and a thickness of 11.1% as shown in Fig. 3.

Figure 3: Cross-section of the E214 airfoil.

The wing shape design made use of several XFRL5 simulations, importing the results from XFOIL (validated code at lower Re associated typically with gliders, similar to Re for the AREND UAS) to make aerodynamic predictions. This together with a Matlab code that includes all the typical wing design trade-offs and was used to determine the wing shape through an iterative process.

The wing designs considered the double-tapered wing only and wing parameters include the wing span, the different chord lengths, the offset for different swept wings, the average chord length and the mean aerodynamic chord length. The computed values from the Matlab code were fed into the XFRL5 tool, which calculates the lift-distribution and the drag polars and diagrams.

There are several options to manipulate the lift distribution of the wing of which only geometric twist and different chord length, realized in form of tapering, have been considered for the prototype wing. Other options like aerodynamic twist and wing swept would become difficult to manufacture using positive-manufacturing technique where the core material is foam. These components can be considered in a future design of the wing when a different manufacturing technique is used. The iterative process, dimensionless parameters and shape of the double tapered half wing resulted in an approximately elliptical lift distribution for the prototype wing design.

The flap design was driven by the requirements of minimal structural weight, of the possibility to de-camber the wing for fast flight, to reduce the stall speed, to manage manufacturing complexity and to limit costs. The stall speed of the wing is 13.7 m/s with a design cruise speed of 20 m/s. Plain flaps were selected and the detailed sizing and design conducted using XFOIL. During the fast flight stage, the aircraft shall be flying a high velocity to reach the search sector quickly to respond fast to any threats. This speed requirement is set to 40m/s, twice the cruise speed.

American Institute of Aeronautics and Astronautics
for which the wing is designed. Plain flaps can be extended upward and thus by lowering the camber the wing creates less lift and thus can fly horizontally with less drag.

The search strategy of the AREND sensor aircraft requires some level of horizontal maneuverability during the observation phase. An aileron design similar to that of a sailplane (which the AREND aircraft resembles) is used and the shape and sizing thereof was driven by the requirements for minimum weight and reduced complexity of control, making use of the Matlab code.

B. Empennage Design

The choice of empennage was a consequence of the decision to use a push-propulsion system. Tail booms and an inverted V-tail offer the advantage of avoiding additional interfaces with the fuselage, which was manufactured in Pretoria (empennage manufactured in Stuttgart). Not only does an inverted-V-tail allow for a drag reduction due to reduced surface area, it also allows the tail to be place outside of the wake caused by the pusher-propeller at the end of the fuselage. Each side of the inverted V holds one control surface and through the upward angle the functionality of the vertical and horizontal stabilizer is mixed. Both control surfaces are always triggered at the same time. The inverted V-tail also has structural advantages, as they are exposed to less bending moments, thus the empennage can be built lighter and the empennage mass will move the center of gravity (CG) of the aircraft further forward.

Since the vertical and horizontal stabilizers are mixed in the inverted V-tail both need to have the same airfoil and only symmetric airfoils can be considered. Similar to the wing airfoil selection different airfoils were selected with the specific requirement of high lift gradients and a high maximum angle of attack. A potential risk is that flow separation from the main wing may reduce the control authority of the empennage control surfaces, which can be investigated with a detailed computational fluid dynamic model.

The HT14 airfoil is selected for the tail at Re of 400,000 because of the stability benefits and the final size of the empennage is achieved after an iterative design process is used (including factors like the high cross winds in the Kruger National Park to ensure optimal camera view). The reference area for the stabilizers, the sizing and geometry for an inverted V-design, the thickness of the tail boom for the link between the wing and empennage, the stability margin of the whole aircraft, the weight of the empennage, the necessary range of the fuselage CG and the necessary servo momentum for deflection of the control surfaces are all designed.

C. Fuselage Requirements and Subsystems

The fuselage of this aircraft serves as a protective and streamlined (low drag) structural container for the payload, control system, parachute system, propulsion system, communication system and landing system. It forms the structural integrator, receiving the wing and empennage loads or the landing skid loads and passing these to all components it carries. From preliminary analysis of the mission parameters the F2-49 shape has been suggested as a suitable low drag body of choice for the fuselage. Implementation and scaling of this shape leads to the size parameters summarized in Table 1.

<table>
<thead>
<tr>
<th>Maximum diameter</th>
<th>Length (Nose to spinner tip)</th>
<th>Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>320 mm</td>
<td>1100 mm</td>
<td>40 liter</td>
</tr>
</tbody>
</table>

Table 1: Preliminary fuselage size parameters.

The AREND fuselage integrates the subsystems (nose gimbal, landing skid, emergency parachute recovery and wing-body interface) which are custom designed for the airframe. In addition a launch device is developed (but not reported on here) since the proposed fuselage does not have a dedicated undercarriage for takeoff.

The nose gimbal housing, designed around the Procillica GT6600 has played an important role in arriving at the proposed size. The 6 main flight batteries require about 3.5 liter of the volume. The emergency parachute recovery system requires about 1.2 liter of the fuselage volume (0.8 liter for the chute and its lines). The prominent landing skid (retracted into the fuselage during flight and collapsing into it during landing) also requires significant internal volume. Otherwise it is component grain size and placement which led to the proposed size.
1. **Fuselage Structural Concept**

The central spine concept (illustrated in Fig. 4) is preferred over the monocoque or the external frame concept. This concept allows for a lighter and easy adaptable aerodynamic skin with no structural responsibility since the central spine and its joining elements is designed to be robust and is protected inside the fuselage (not exposed). Maintenance, integration and assembly are comparatively easy on the spine concept because changes in arrangement and components are easy to implement by simply changing their connection brackets. A modular approach becomes easy to implement.

![Figure 4: The fuselage based on the low drag body shape (F2-49) with the nose adapted for the gimbal.](image)

2. **The Nose Gimbal System**

Visual sensors form the primary challenge in this project. High quality sensors form the primary reason for this airborne system to be developed. Of the all-up mass of 18 kg a substantial portion, 3 kg, are to be dedicated to the payload. The cameras on the gimbal make a significant contribution to this load. Therefore, as part of the airframe structure, the gimbal structure is part of the fuselage design since appropriate load paths and load factors need to be considered in the structural design to hold the rather heavy cameras. The gimbal system is a dedicated system and an off-the-shelf structure was not considered, since the gimbal fairing is an integrated part of the fuselage aerodynamic fairing. In addition the location of the gimbal camera offers the pilot view especially for landing which has the highest risk of failure. In addition the nose gimbal allows for a belly landing without direct impact to the expensive payload.

The two-axis arrangement of the camera in the gimbal does not allow full stabilization and this may lead to image slur which may render such images useless. Next to the image processing system, the next most important aspect of this project is the challenge of the sensor stabilization and control. While the 3-axis arrangement should be superior in terms of image orientation and stabilization it does introduce problematic structural layout and load path challenges which would lead to a larger and heavier fuselage. Should the 2-axis arrangement prove to be insufficient a payload design based on the more difficult alternative can be attempted.

3. **The Landing Strategy**

The landing of a UAS presents the most challenging phase of flight. The success and the cost of UAS operations depend largely on the success of the landings. UASs are still lost at unacceptable high percentage due to landing incidents. For that reason the design of the landing systems has received high priority in the design and development of the AREND airframe.

The touch-down and ground run constitute the process of absorbing the terminal energy of flight. The undercarriage will need the facility to absorb energy however it does not need to provide any means of offering low rolling resistance. It must however be able to accommodate terrain roughness. The touch-down process needs to be
considered as one in which the objective is to change the momentum of the aircraft from the approach vector into a horizontal vector (or rather parallel to the ground) with a minimum force on the airframe.

Two principal height dissipation concepts are considered:

i) normal approach (in which normal flight drag dissipates the energy of height)

ii) emergency recovery (in which some other means is involved in dissipating the energy of height)

The rationale for these two choices is as follows.

i) Normal approach: Skid landing

A normal landing is done by rounding out after the approach to fly parallel to the ground just before touch down, making use of an undercarriage which does not require the landing flare to be performed. In this case the landing is called controlled flight into terrain (CFiT) and this would be at the approach speed and the approach angle. Onboard landing system was preferred to the ground based landing systems since not all landing scenarios can rely on a ground based facility. There are multiple risks with this landing strategy which need to be addressed during the design phase. Some of these include the uncertainty of the landing area, the exact proximity from the ground, load paths through the structure on impact, ground looping and damage to the aircraft and sensors.

A single central extendable skid rather than a fixed skid on the fuselage was chosen as the on board landing system. This approach is expected to reduce the possibility of ground looping, offer protection to the payload in the nose gimbal, can easily be accommodated in the fuselage and has a direct load path to the CG of the aircraft. Figure 5 shows the concept of the proposed kinematic arrangement which uses a gas strut as the deployment activator and the energy absorber.

![Figure 5: Conceptual representation of the extended skid showing the extended gas strut and showing a detail design of the rear strut in the retracting position.](image)

ii) Emergency recovery: Parachute emergency landing

UAS operations legislation is likely to contain requirements for emergency recovery, since flight may have to be terminated at any stage or location. Additionally the expensive payload can be recovered if an emergency recovery system is available. It is therefore conceivable to land the system by default by means of this recovery system. A well refined recovery system may offer the easiest and most reliable landing strategy.

This event would relate to a case where the aircraft is unable to be flown, either structurally or for being out of control. This is the final backup of the aircraft. Scenarios when flight may have to be terminated by an emergency recovery are:

- loss of communication beyond the allowed time laps
- loss of control from the ground
- loss of control by the autopilot
- critical system failure
- critical structural failure

In any such event the recovery command is issued autonomously or by means of a ground command and the recovery procedure kicks in immediately. In this case also the energy of the flight altitude above ground needs to be
managed. During emergency recovery it is assumed that no control is available over the approach. The approach here is typically the descent on a parachute with the approach angle taken as essentially vertical.

A pneumatically activated parachute emergency recovery system (ERS) has been developed for the AREND UAS. The ERS consists of a pressure vessel which acts as a pushrod inside the central spine of the fuselage with the payload bay (camera gimbal, image processor and storage and battery) mounted on the front. This module is a replaceable unit and here it acts as the deployment projectile with an estimated mass of 3kg. Upon activation the pressure is released into the barrel by which the entire payload module is shot out by means of the barrel. It accelerates in the barrel until it leaves the barrel with muzzle velocity. It then has sufficient kinetic energy to deploy the parachute in any scenario of aircraft attitude and speed. The system was developed by testing individual components first and then building a full system to experimentally test the theoretical dynamic model. This procedure lead to multiple risks being mitigated in terms of off the shelf components used in the system as well as ensuring the theoretical design was sound before integration into the fuselage which is the next step. The primary risk in this system is whether the system would provide enough force to split the fuselage apart, extract the parachute from the spine and travel a sufficient distance away from the aircraft to avoid entanglement with the parachute rope.

D. Wing-Body Interface

The wing and fuselage is required to disconnect easily into smaller pieces. Joints inevitably cause additional mass, due to in part because of regulation on joints requiring a much higher safety factor than otherwise in a structure. Joints also involve more complex load paths. The AREND airframe makes use of a three part wing with a shear joint to the fuselage to allow the main spar to be one uninterrupted structural unit and all wing parts have a similar length, useful for packaging. It also ensures that only a shear introduction needs to be provided between the wing and the fuselage, outer wing joints can be light since they have lower bending moments and outers wings can be made as replaceable elements. The joint between the outer wings and the inner section become sacrificial joints to help mitigate the risk of losing the full wing during the CFIT landing. Figure 6 depicts the structural connection point between the central spine of the fuselage and the mid-section of the wing.

![Figure 6: Internal connection point between the fuselage and the wing (shown upside down as in load test).](image)

The three separated wing segments and with the tail boom connection in the wing allowed limited space for the flaps. In order to reduce weight the flap functionality were divided into two parts, one between the fuselage and the tail boom and the other between the tail boom and the end of the inner wing section. Both parts are connected with a U-shaped wire around the tail boom and are actuated by one control servo. This allows for a larger flap area with only one servo. To further enlarge the flap area the depth of the flap was set to be 30% of the wing chord.
A radio controlled flight test of the wing and empennage lead to a couple of design adjustments in terms of the tail boom lengths and CG of the aircraft. It also allowed for first order estimations of the ease of control of the configuration.

Design and construction of the three part wing section was completed at the University of Stuttgart and brought to South Africa for testing. Structural wing testing was done at the CSIR in Pretoria. The test demonstrated that the design requirements were validated and fabrication was successful in meeting the design requirements.

III. Embedded Systems

A. Embedded System Overview

The driving requirements for the embedded system design largely align with the operational requirements for the entire system: quickly and silently deliver a payload within the search sector, support modular payload sensors and provide user-friendly controls while complying with local and international laws and regulations. In order to achieve these requirements, the embedded system shall provide manual radio control with autonomous capabilities, maintain a communication link within a 30 km radius search sector, support modularly implemented payloads and minimize drag impacts on the airframe from embedded system components.

To allow for modular sensor payloads, the embedded system is divided into two major subsystems: the primary flight control subsystem and the variable payload subsystem. The primary embedded subsystem consists of the propulsion system, the autopilot and flight control system, the communication link for manual control and the primary power distribution system. The payload embedded subsystem consists of the payload sensors, the camera gimbal and a dedicated power distribution system. The data communication link and payload processor are shared between the primary and payload embedded subsystems for telemetry and sensor data downlink and to integrate payload sensors with flight controls, respectively. Figure 7 displays the primary subsystem components, payload subsystem components and components shared by both subsystems, along with the data and power flow.
B. Flight Control System

The flight control system for the aircraft must allow for manual radio control of the aircraft for takeoff, landing and emergency situations, but must also provide autonomous capabilities for an end user with minimal training. Furthermore, the flight control system must be able to handle the high wind speeds often found in Kruger National Park. Because of the complexity of designing a fully-capable autopilot, a commercially available autopilot is used for the flight control system. The open-source hardware “Pixhawk” autopilot, manufactured by 3DRobotics, is widely used in the academic and hobbyist communities for unmanned aircraft because of its modularity and community support and is thus selected for this design. The open-source PX4 Flight Stack project\(^3\) is used for the flight control software.

The PX4 uses a 22-state extended Kalman filter (EKF) to estimate position, velocity and attitude of the aircraft and utilizes separate controllers to achieve the desired attitude and position. To fully utilize the EKF, navigational sensors are required to measure the aircraft states. The Pixhawk autopilot contains an embedded 3-axis gyroscope, a 3-axis accelerometer/magnetometer and a 3-axis accelerometer/gyroscope for attitude and velocity estimation, as well as a barometric pressure sensor to measure altitude. A GPS receiver with a 3-axis compass is used for global position and attitude estimation. A pitot-tube probe is implemented on the leading edge of the aircraft wing to directly measure airspeed, which is required for the PX4 software to estimate the wind vector by comparing airspeed and groundspeed from the GPS. Knowledge of the wind vector will allow for softer landings and thus minimize the risk associated with the landing skid design, as the aircraft will fly into the wind on landing to lower ground speed while maintaining the minimum airspeed. A laser rangefinder with a range of 60 m is used to obtain a more accurate measurement of altitude above ground level to assist with manual landings and allow for future autonomous landings.

A significant risk associated with using a commercial-off-the-shelf autopilot arises from the ground up design of the AREND aircraft. The Pixhawk autopilot is intended for use in either ground rovers, rotary wing aircraft, or fixed wing aircraft and provides pre-programmed settings for many common configurations. However, the inverted V-tail...
empennage design is not one of these available configurations. Thus, hardware-in-the-loop (HITL) testing of the autopilot will be performed on the ground after the embedded system is integrated with the aircraft to ensure the autopilot correctly actuates the control surfaces of the empennage.

C. Propulsion

The propulsion system must provide the thrust required by the airframe to achieve the maximum flight speeds of 72 km/hr. Also, the propulsion system must maintain an audio horizon sufficiently above ground level to avoid detection by poachers. Furthermore, the propulsion system must achieve a minimum flight range of 90 km, which allows delivery of a payload to the most extreme way point within the 30 km radius search sector, execution of a 30 km search pattern and returning to the launch point. The maximum flight range must be less than 300 km to avoid the system becoming ITAR restricted and thus requiring a permit from the U.S. government to export to South Africa.

Since the camera gimbal is located in the nose of the aircraft, the propulsion system must use a pusher-prop configuration. The main source of noise generation for the aircraft results from the power plant used to actuate the propellers as well as the rotational speed of the tips of the propeller blades. Thus, an electric motor was selected to minimize noise and the propeller blades are designed to be as short as possible while providing the required output power in order to minimize tip speed. For an electric propulsion system, the operational voltage must be less than 28 V to avoid being ITAR restricted and thus requiring a license to export outside the U.S.

With these requirements in mind, an analysis was performed using the “Advanced Aircraft Analysis” (AAA) software tool for the airframe to determine that a minimum propeller output power of at least 0.79 kW is required to achieve the desired cruise speed. The online tool eCalc is then utilized to compare various electric motors and propeller combinations to achieve the required mechanical output power. The selected design uses the Tacon Bigfoot 160 electric motor and a 5-blade, 16 x 13 propeller. The eCalc analysis estimates that a motor input power of 0.95 kW is required at 89.3% efficiency to achieve an output mechanical power of 0.846 kW, which is greater than the 0.79 kW requirement obtained from the AAA program. The expected current draw from this analysis is 65 A at 22 V and results in a static thrust of 53.17 N.

The pusher-prop configuration and intended landing method of using the reinforced skid to land anywhere in the bush presents a significant risk of ground strikes to the propeller. The use of five, short propeller blades helps mitigate the risk of ground strikes, however there is still a chance that the landing area is not completely clear of rocks or bushes that can catch and break the propellers. Folding propeller blades are thus used to prevent ground strikes from occurring. The centripetal acceleration of the motor causes the blades to extend while the motor is rotating and pressure from the airflow over the fuselage causes the blades to fold back when the motor throttle is cut just before landing.

D. Power System

The main requirements for the aircraft power system are derived from the expected current draw of the motor and the required flight endurance, which is derived directly from the required flight range and flight speed. Additionally, the power distribution system must be capable of supporting modular payloads. This requirement for modularity drove the decision to utilize two separate power systems on board the aircraft: the primary power system and the payload power system. Utilizing two separate power systems also allows for power redundancy on the autopilot and flight control system, thus allowing the embedded system to operate the emergency parachute if the primary power system fails.

Since the propulsion system is electric, batteries are used for both the primary and payload power system. Lithium-polymer (LiPo) batteries are selected because of their high power density and low cost. The standard voltage for LiPo cell is 3.7 V, so a 6-cell LiPo battery pack nominally charged to 22.2 V is used for the primary power system to satisfy the intended operation voltage of 22 V for the electric motor. For the payload power system, the battery voltage must be sufficient to power a variety of sensors that could be implemented on the aircraft. Many sensor technologies operate at 3.3 V, 5 V and 12 V, as was the case for all the sensors considered so far in this
design and thus a 4-cell LiPo battery pack is utilized for the payload power system providing 14.8 V. Battery eliminating circuits are then used to drop the voltage to the required levels for each sensor. Furthermore, these battery eliminating circuits regulate the voltage supplied to the sensors, allowing the power system to provide a constant voltage even as the LiPo battery voltage drops throughout the charge cycle.

E. Payload System

The payload system is required to support a permanent camera gimbal in the nose of the aircraft, as well as a variety of payload sensor that could be placed on the aircraft. Mission requirements state that the aircraft must provide near real-time alerts to poaching activities within the park. Because of the length of a mission and the difficulty of a human spotting a target in the South African bush, image processing must be used to analyze the camera images for potential poaching threats. Since the resolution of the cameras required for any image processing results in a very large amount of data, image processing shall be performed on-board the aircraft and only downlink select images for human verification.

The camera selection was performed by considering the requirements of the image processing algorithm. Johnson’s criteria\(^4\) attempts to quantify the number of pixels covering a target in an image that is required to detect, recognize and identify (DRI) an object in the image and requires 8 pixels across a target to enable identification. These criteria were developed prior to computer image processing and a white paper\(^5\) from the security firm AIS Security Solutions recommends at least five times Johnson’s DRI to accurately detect, recognize and identify a typical sized man for common image processing algorithms. Thus, it was determined to size the camera such that a 0.5 m x 0.5 m target would be covered by 40 pixels for a search altitude of 300 m. The camera selected is the Prosilica GT6600C, which has a resolution of 28 megapixels providing 67 pixels on a target and a ground line separation between pixels of 6.11 cm. Considering the search speed of 20 m/s and the cameras frame rate of 4 frames per second, a 0.5 m x 0.5 m target will be in view for 55 consecutive frames over 13.9 s.

In order to perform the image processing on-board and allow for the implementation of a variety of sensors, the NVIDIA Jetson TK1 was selected as the payload processor. The Jetson TK1 operates a version of the Linux distribution Ubuntu and has a graphical processor unit intended for computationally intensive graphics and image processing. The Jetson TK1 also has a wide variety of inputs and outputs to interface with various payload sensors and communicates with the camera over GigE (1000 Mbps) Ethernet protocol.

To improve the autonomous capabilities of the aircraft system, the payload processor hosts a local command-line GCS for the Pixhawk autopilot called “MAVProxy”. MAVProxy is a Python based GCS that, along with the Python module “DroneAPI”, allows for custom mission scripting. Telemetry data from the autopilot will be transmitted to the remote GCS as well as the local GCS on the payload processor. This allows the payload processor to monitor the state of health (SOH) of the aircraft, which in turn allows the human observer at the remote GCS to focus more time on monitoring payload sensor data. Furthermore, data from the payload sensors may then be utilized by the payload processor to make decisions and autonomously command the autopilot. In Fig. 8, the diagram on the left shows the interface between the payload sensors, payload processor and autopilot; the diagram on the right shows an example decision making sequence incorporating payload sensors with mission planning.

American Institute of Aeronautics and Astronautics
F. Communications System

The primary requirements for the aircraft communications system are to establish a constant radio link within the search sector (30 km range) and to comply with South Africa broadcasting regulations, which are set by the Independent Communications Authority of South Africa (ICASA). The options considered were a ground based Line of Sight (LOS) system and satellite communication links. While satellite communication provides the greatest range, the large mass, cost and power requirements of SATCOM along with low bandwidth drove the decision for a ground based LOS system.

The flight control system requires two communications links with the ground station: a radio control link with the pilot for manual control and a data link for telemetry downlink and uplink of commands. The communication links must be placed on the international Industrial, Scientific and Medical (ISM) frequency bands in order to operate the aircraft without a license from ICASA. The ISM bands are 433 MHz, 2.4 GHz and 5.8 GHz for South Africa. The 433 MHz band has superior propagation characteristics with regard to foliage penetration and free space loss. For this reason and since manual control of the aircraft is more important than sensor and telemetry data, 433 MHz was chosen as the uplink carrier frequency. Conveniently, the 2.4 GHz band is better suited to handle the high data rate requirements of the telemetry and sensor data downlink because of the larger bandwidth. While the 5.8 GHz band provides an even larger bandwidth than the 2.4 GHz band, the free-space loss is much greater because of the faster frequency and shorter wavelength and thus 2.4 GHz is selected as the carrier frequency for the data link.

Furthermore, the communication system must be able to resist possible electronic sabotage by the poachers, such as frequency jamming or hacking into the data link. To mitigate jamming, both communication links shall use frequency-hopping spread-spectrum (FHSS) technology, in which the transmitter changes frequency in a pseudo-random pattern to prevent an unwanted observer locking onto the carrier frequency. Also, the data and telemetry link shall employ AES encryption to prevent poachers obtaining valuable sensor data or control of the aircraft.

The radio system chosen for the uplink is the “Immersion” RC EzUHF transmitter and receiver pair, which is a FHSS radio system on 433 MHz. A “Turnigy” 9XR radio controller provides an 8-channel pulse-position modulation (PPM) signal to the EzUHF transmitter and receiver, which is the expected control input for the Pixhawk autopilot. The eight channels allow the pilot to control the throttle, control surfaces, parachute and landing skid, as well as change the flight mode of the autopilot between manual and autonomous modes. This feature of flight mode switching from the pilot controller, required by the PX4 autopilot software as a safety precaution, presents the greatest security risk to the aircraft embedded system. Since the manual control link is not encrypted, a poacher would only need to determine the frequency hopping pattern of the specific transmitter being used in order to assume manual control of the aircraft. To prevent this, the PX4 software can be modified to remove the flight mode switch, however this work must only be performed after the embedded system has been fully tested and the pilot no longer requires immediate access to the flight mode switch in case of an embedded system failure.
The data link radio system used is the “FreeWave” WavePoint 10e, which is a FHSS radio system with a 2.4 GHz carrier frequency that allows for 256-bit AES encryption. The WavePoint radio supports point-to-point and point-to-multipoint operations, allowing for the intended concept of operations with a central control station as well as the possible introduction of communication relay towers to extend the range of the aircraft system.

IV. Ground Wireless Sensor Network

A. Concept and Design

The AREND project is a system of systems approach to provide a counter-poaching technology. It provides a higher efficacy to apprehend poachers before they kill. Therefore the concept of operations requirement for the aircraft includes one subsystem on the ground which helps in the decision making process to dispatch the aircraft to a specific location where the ground sensors suggest a possible poaching effort. The requirement for a ground network is important due to the vast park areas that require surveillance. An “uninformed” flight path over a surveillance area has a high risk of failure to detect any poaching activity; thus such effort will be worthless and wasting valuable resources. The AREND ground wireless sensor network (GWSN) is a distinct support system with the purpose of providing threat detection, classification and location information to the AREND UAS aircraft system, park rangers and other approved stakeholders and systems. Signals from the GWSN can guide the aircraft operating team to send the aircraft off to an area where the ground sensors indicate unusual activities. This concept of operation is likely to have a higher success rate in preventing poaching or apprehending poachers. It also justifies the aircraft design requirement discussed above to fly at high speed to the area of interest and when there, fly at low speed to do intelligence, surveillance and reconnaissance (ISR).

1. Data Flow

The basic concept of the GWSN system is to collect data via sensors deployed by rangers in the park, transport that data to a central server and process it to facilitate the detection, classification and location of potential poaching activities in the area. This data may be collected from a variety of sensors implementing technologies such as acoustic, seismic, optical, proximity and radio frequency sensing. After collection at a particular point, called sensor node, the GWSN then forwards this data on to an intermediary data sink, called master node over its own local network. This master node then acts as a gateway between the local network and the GSM network, using the latter as a backhaul link to forward the data to a central server for storage, processing and retrieval via a RESTful API (application program interface). Each dataset forwarded contains sensor samples, GPS (global positioning system) coordinates of the sampling location (determined and assigned to each sensor node at deployment) and the time of samples were logged. An overview of GWSN data flows is given in Fig. 9.
Figure 9: Ground wireless sensor network data flows.

The GWSN supports both early warning and rapid response scenarios. In an early warning scenario, the aircraft is not on mission and the GWSN’s primary support function is to facilitate the detection, classification and location of previously unknown potential threats, i.e. “poaching events”, which in turn may be used by AREND UAS dispatchers to form a decision to send the aircraft on a reconnaissance mission. In a rapid response scenario, the aircraft is on mission and the GWSN’s primary support function is to facilitate the detection, classification and location of ongoing poaching events in order to help narrow down the aircraft’s search footprint.

2. Networking

The GWSN is a wireless sensor network employing a mesh topology with multiple end nodes and a single master node. Data collected by sensor nodes are routed to the master node via other sensor nodes en route in a multi-hop fashion. The mesh topology is both self-organizing and self-healing: the network can discover new nodes and detect new paths as well as re-configure itself in response to the addition or subtraction of sensor nodes. This provides a high degree of robustness and scalability, allowing for “drop-in” network deployment and protection against individual sensor node failures.

The master node functions as the mesh network’s coordinator and data collector as well as a gateway for backhaul communications. As coordinator and data collector, the master node is responsible for forming the mesh network, temporarily storing its sensory data and acting as a gateway and backhaul link to and from the central server. By concentrating these essential functions, the master node offloads most risk from other nodes, but also creates a single point of failure for the network. Mitigation of this risk would be to deploy additional nodes with the necessary hardware either as active sensor nodes or as inactive “reserve” nodes and activated remotely via a control message or over-the-air firmware update when needed.

The backhaul portion of the GWSN provides an uplink and downlink between the mesh network deployed on the ground and web servers and services via intermediary GSM/3G networks. The GWSN’s master node includes radio modules for communicating both with the mesh sensor network protocol and with available GSM/3G networks over IP (internet protocol) and acts as a gateway to translate between these protocols.

GSM/3G networks were chosen for backhaul as they leverage existing infrastructure, reduce the need for additional large and high-power antennae and enable simple and dependable drop-in networking capabilities wherever coverage is available.
3. Deployment

A main consideration for the GWSN is its ability to be re-deployable to follow the migration and territorial patterns of the rhinoceroses and poachers and to enable the re-use of invested equipment assets. As any field operation includes many risks for personnel, it is important that installation and uninstallation of the GWSN is quick, simple and requires little to no onsite setup. Furthermore, all nodes in the GWSN must be as discreet as possible to avoid detection and tampering by both poachers and inquisitive wildlife. Lastly, all equipment must be able to operate continuously for months at a time under the stresses of the park’s climate and weather.

GWSN sensor nodes are to be packaged in weather-proof casing with only sensing components and antennae external to the case. Sensor nodes may then be deposited below ground with only antennas and sensing components breaching the surface, if necessary. If possible, sensing components such as geophones may also be deposited below ground. The sensor nodes’ small size ensures very little time and work is required for installation. By minimizing the exposed surfaces of GWSN equipment, camouflage requirements for these surfaces are also minimized.

Efforts are made to allow the network’s master node to be installable underground, but aboveground installation may be necessary. The GWSN’s mesh topology and ability to be remotely configured also allow for “drop-in” networking with little to no onsite setup, minimizing the time personnel spends in field operations.

The GWSN prototype network may deploy in a picket-fence configuration, with sensor nodes forming a perimeter around an area of interest so that their sensor coverage areas form a linked chain. This provides end-to-end sensor coverage along a path with high probability of detect poachers that cross it. Probability of successful detection may also be improved by overlapping sensor coverage areas, aka electronic “fences”.

This configuration does not support determination of a poacher’s trajectory without multiple fences or prior knowledge of the poacher’s origin. However, it is appropriate for the GWSN’s particular environment as it is most suitable for deployment around small areas of interest and does not require extensive scale and numbers to detect poaching activity in these “hotspots” effectively.

B. Prototype Implementation

As a proof of concept, a prototype version of the GWSN was implemented and tested in Helsinki, Finland. A sample set of collected sensor data was also processed (see below) to demonstrate the feasibility of automatic threat-detection based on analog seismic sensor data.

The mesh network of the prototype was implemented using the ZigBee specification (PRO feature set) in the 2.4 GHz ISM band. Digi XBee PRO S2B radio modules were used. Based on an empirically-tested median throughput rate of 2.15-3 kbps for encrypted ZigBee packets, a maximum analog sampling rate of 10-bit samples was enforced at 200 Hz. One drawback to using ZigBee for a remote network like the GWSN is its lack of support for sleeping router nodes. This essentially forces the RF operations of any node acting as an intermediary hop between others in the mesh network to use a very high duty cycle, greatly increasing its power consumption. To help alleviate this drawback, each sensor node was programmed to dynamically switch roles between an “always-on” router node and a “sleeping” end-node capable of very low duty cycles. Switching between these roles is triggered with a simple command sent from the master node. Furthermore, sensor nodes equipped with the proper additional hardware (i.e. a high-capacity power supply and GSM module) are also able to switch their role to that of a master node with a simple over-the-air firmware update of the radio module, although this incurs many side-effects to forming and coordinating a new ad hoc network that have not been fully explored. In both role-switching cases, however, the microcontroller unit’s software is able to detect the change in roles and effectively act as either master node, router node, or end-node with no re-programming necessary.

To further lower power consumption, prototype sensor nodes also employ independent sampling and radio frequency (RF) operations, adaptive polling rates and external wake-up via a trigger. Independent sampling and RF operations ensure that periodic events such as quick-sampling and parent polling may occur at frequencies optimized to balance power consumption and threat detection. Adaptive polling rates allow for very low network duty cycles and long sleep times between polls when no activity is detected and higher polling rates when maximum network use and efficiency is required. External wake-up via trigger allows the microcontroller to sleep until an event requiring processing occurs. The wake-up trigger may be either a digital sensor (e.g. a passive infrared sensor detecting movement) or an incoming transmission from the radio module.
Backhaul communications between the master node and central server were implemented over GSM facilitated by a Seeed Studio GPRS Shield V2.0. Sensor and network data from the prototype GWSN are compressed and sent to a Linux Apache central server via GSM as HTTP POST requests. A server-side script then parses, decompresses and updates a MySQL database based on the data received. Once sensor data has arrived from the GWSN, it is immediately made available to authorized stakeholders and/or additionally processed to help detect and classify threats and poaching events.

C. Threat Detection Testing and Results

As part of a proof of concept for post-processing of sensor data to detect and classify threats, raw analog geophone data was recorded and processed to detect human footsteps as a proxy for a potential poaching event. (Processing was based on frequency spectrum analysis techniques proposed by Kenneth Houston and Daniel McGaffigan.) First, a geophone recorded seismic data in a grassy area at 200 Hz while a man walked a straight line from the sensor to a distance of 10 m and then back. The raw sample data retrieved from the GWSN was then bandpass filtered to attenuate signals outside of the 10-40 Hz band of interest where the seismic signals of footsteps tend to appear. Next, the data was rectified and decimated to generate an envelope that was in turn used to produce a high-resolution Fast Fourier Transform (FFT) in the frequency domain for detecting the periodicity of footstep signals. This FFT data was then passed through a two-pass split-window (TPSW) filter to estimate background noise and this noise was used to estimate the signal-to-noise ratio (SNR) of the signal’s FFT.

The criteria for classifying a sample set as containing footsteps was as follows: if the frequency of the footstep signals is within the expected range (1-3 Hz) and the SNR magnitude of the primary footstep frequency and its first harmonic are above a certain threshold (again based on the work of Houston & McGaffigan), then human footsteps may be considered detected. Given these criteria, our GWSN with subsequent signal processing was able to successfully detect human footsteps for the given sample as shown in Fig. 10. This proof of concept demonstrates how a system of systems approach can greatly increase the efficacy of UAS-based anti-poaching efforts by providing the aircraft system in the air with real-time locations of potential poaching events detected on the ground.

![Figure 10: Frequency-domain signal processing of seismic data collected from the AREND GWSN.](image-url)
V. International Collaborations

The AREND project was started under the leadership of Prof. J.N. Koster after an invitation by the Wildlife Conservation UAS Challenge (www.wcUAVc.com) established in 2013. The Challenge was to foster innovation and invention in the design, fabrication and utilization of unmanned aircraft to assist with counter poaching and illicit wildlife trafficking. It calls on students, hobbyists, academics and corporations to cooperate in a Design, Build, Fly challenge that emphasizes the integration of sensors, embedded systems and communications in a robust and high endurance aircraft.

Rampant wildlife poaching of rhinoceros and elephants has been termed the “African Crisis” in many reports. Rhino poaching is a key concern for South Africa and specifically for Kruger National Park (KNP) as there has been an exponential growth in poaching and rhinos face extinction. This park lies along the Mozambique border and struggles to protect its rhinos from well-organized poacher networks that infiltrate the grounds. Rhino horns are illegally sold for their supposed medicinal purpose in Vietnam and China and are currently worth more per gram than gold. Patrolling an expanse of 19,633 km² with a small number of rangers is impossible and previous unmanned aircraft have often proven ineffective in KNP’s environment. Rangers need additional help and an unmanned aircraft system network may provide a technological solution.

As wildlife poaching is becoming a humanitarian problem considering that rhinos and elephants are now predicted to become extinct within 5-10 years, the project AREND was established as an international team of students at four universities on three continents. The universities are: the University of Colorado Boulder, United States; the Helsinki Metropolia University of Applied Sciences, Finland; the University of Pretoria, South Africa; and the University of Stuttgart, Germany. These four teams provide complimentary technical skills, as seen in Fig. 11, while the Pretoria team has the additional contact to the Kruger National Park organization. The University of Colorado and the University of Stuttgart have cooperated before on a global collaboration project HYPERION® which provided many lessons learned that benefited project AREND.

![Figure 11: Individual university team contributions.](image)

Nevertheless this project AREND was different in that individual teams acted more independently on a specific job defined by the team during weekly global conferences. Each team worked on the tasks assigned for the week and reported at the following meeting. The work by all individuals was made available for assessment and contribution to all team members on a cloud file system. The weekly meetings usually lasted for 60-90 minutes. At special milestones the conferences lasted for several hours and were handled more formally by inviting advisors and sponsors. This was the case for the Preliminary Design Review (PDR), the Critical Design Review (CDR) and for special needs such as familiarizing new students with the overall design.
The Pretoria team was selected as the leaders for the final test flights of the AREND aircraft as they can provide the environment considered for the design criteria and because the anti-poaching application benefits those issues that are of highest interest to the people of South Africa. Flight tests are planned for December 2015.

Lessons learned in this project confirmed many lessons from the Hyperion project. One caveat in this independent global team organization is that the project’s systems engineer has a more difficult job to understand the system engineering process developed by the individual teams. The global project manager, as we learned before, has to have excellent personal skills to develop a successful collaborative work environment.

VI. Conclusion

AREND is an international project to develop a sensor aircraft that can be equipped with a selection of sensors which should help detect wild animals, such as rhinos and elephants and poachers. The operational goal is to help prevent poaching of wildlife and to help rangers apprehend the poachers. The team is composed of graduate students from four international universities on three continents. The learning was not limited to systems engineering design of a small aircraft but also an opportunity for the students to learn some skills in global research and development collaboration, which is of interest to global technology corporations.

A few generations of students had the opportunity to participate in this project initiated around a set of requirements. Developing these requirements was the first task, followed by analytical analysis and understanding of technical risks as well as project management risks. The design effort was successful and the flight tests of the aircraft are scheduled for December 2015.

The prototype airframe has been used for initial structural, integration and flight mechanical testing during which system individual designs were confirmed or adjusted and integration between subsystems could be adapted if necessary. The next design phase will be to redesign the wing in order to manufacture a lighter but still structurally viable wing and empennage. In order to mitigate some of the potential risks of the wing and empennage aerodynamic interference and the effects of control a computational fluid dynamics model as well as a flight mechanic model will be used to analyze the system.

The landing phase of the aircraft has the highest risk of failure. The proposed skid landing device will be tested individually, after which it will be integrated into the aircraft for further structural testing. Several sacrificial joints will be used throughout the structure to ensure the aircraft can be reassembled after a controlled flight into terrain.

The embedded system has been designed to achieve modularity, in terms of interfacing with various payload sensors and as well as overall mission design. The open-source autopilot software and on-board flight processor allows for custom mission scripting to adapt to the constantly changing poaching methods. The significant risks to the embedded system result primarily from the communications system, and future work will focus on designing antennas into the airframe to improve signal reliability as well as performing detailed analysis of the line of sight communication network within the Kruger National Park. Future work shall focus improving the autonomy of the UAS, as well as implementing payload sensors that can improve the threat detection capabilities of the AREND system. For instance, infrared cameras may be utilized to provide image data during night-time operations. The feasibility of using infrared cameras to detect poaching operations in the Kruger National Park must be further investigated, as the extreme heat in the park may reduce the value of infrared images.

The ground wireless sensor network prototype has been implemented to transfer data from an analog seismic sensor through the sensor network, and post-processing of the data was performed to prove feasibility of using these sensors to detect poaching threats. The design for the ground wireless sensor network allows for easy implementation of the sensor network within the park to mitigate risks associated with construction and implementation of the network. Further testing must be performed in the operational environment in South Africa to ensure reliability of the threat detection and networking procedures.

American Institute of Aeronautics and Astronautics
Acknowledgments

Students: The project was of interest to many students. Some contributed as part of regular course work or independent studies. Some students joined the team for only one semester whereas others stayed on the team for multiple semester. Here are the names of the participating students; their contributions are greatly appreciated.

CU-Boulder: Ryan Arndorfer; Anuraag Bodi; Cameron Brown; Jefferson Caffery; Nicholas DiOrio; Christine Fanchiang; AJ Gemer; Justin George; Luis Gonzalez; Krishna Kakarla; Laura Kruger; Andrew Levine; Benjamin Martin; Casey Meyers; Nilendra Nimbalkar; Kumar Prasanna; Nikhil Shetty; Tyler Smith; Saurav Srivastava; Kazuo Yonekura; John Russo; Chris Womack; Matt Busby.

MU-Helsinki: Nikita Korhonen; Balázs Kovács; Rasmus Pettersson; Antti Toura.

UP-Pretoria: Byron Coetser; Warren Du Plessis; Jeandre Du Plessis; Mathieu Gayot; Sune Gerber; Karl Grimsehl; Michael Kruger; Armand Leibbrandt; Riaan Meeser; Ewald Taljaard; Jakob van Tonder.

US-Stuttgart: Tim Baur; Rick Lohmann; Tariq Özyurt; Tim Wegmann.

Advisors: The AREND project had the fortune to receive strong guidance from professionals throughout the project.

Matt Bracken, anti-poaching ranger; Jason Coder, NIST; Dr D. Cooper, EKZN (Ezemvelo Kwa-Zulu Natal Wildlife); Hans Grobler, University of Pretoria; Dr. C Harper, University of Pretoria; Prof. W. van Hoven, University of Pretoria; Rebecca McCloskey, Denver Zoo; John Monk, CSIR, Pretoria; Dipl. Ing. Holger Kurz, University of Stuttgart; Dipl. Ing. Dominique Bergmann, University of Stuttgart; Dipl. Ing. Jan Denzel, University of Stuttgart; Charlie Lambert, SkySentry LLC; Phelps Lane, Helios Torque Fusion; Prof. Claus-Dieter Munz, University of Stuttgart; Alexandra Musk, University of Colorado; Aliyah Pandolfi, Wildlife Conservation UAV Challenge; Dean Paschen, First RF Corp; Dr. Antti Piironen, Metropolia University; Anna Rivas, Denver, Colorado; Hennie Kieser, CUAASA; Eric Schmidt, Wildlife Protection Solutions, Denver; Dr W Uys, AirWing of Game Reserve Unite; Ian Lester, Beyond Wireless Technology; Steve Cass, FreeWave Technologies; James Mack, University of Colorado.

Wildlife Protection Solutions (WPS), a Colorado 501(c)(3) not-for-profit organization dedicated to the conservation of endangered species, led our crowdfunding campaign. The Kickstarter donors made this project possible and all contributions are greatly appreciated. Partial funds were distributed to the Metropolia University of Applied Science, the University of Pretoria and the University of Colorado. The University of Stuttgart provided their own funding contribution for the wing fabrication. The Universities of Stuttgart, the University of Pretoria and the Metropolia University have also contributed significant in-kind contributions to the project. The University of Colorado Engineering Excellence Fund contributed additional funds in support of student travel to South Africa where flight testing was performed in November and December 2015.

References

3 PX4 Flight Stack, Software Package, Meier, L., Computer Vision and Geometry Lab, ETH Zurich.


