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Sensing Through the Continent: Towards Monitoring Migratory Birds Using Cellular Sensor Networks

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Sensing Through the Continent: Towards Monitoring Migratory Birds Using Cellular Sensor Networks

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ABSTRACT

This paper presents CraneTracker, a novel sensor platform for monitoring migratory birds. The platform is designed to monitor Whooping Cranes, an endangered species that conducts an annual migration of $4,000$ km between southern Texas and north-central Canada. CraneTracker includes a rich set of sensors, a multi-modal radio, and power control circuitry for sustainable, continental-scale information delivery during migration. The need for large-scale connectivity motivates the use of cellular technology in low-cost sensor platforms augmented by a low-power transceiver for ad-hoc connectivity. This platform leads to a new class of cellular sensor networks (CSNs) for time-critical and mobile sensing applications. The CraneTracker is evaluated via field tests on Wild Turkeys, Siberian Cranes, and an on-going alpha deployment with wild Sandhill Cranes. Experimental evaluations demonstrate the potential of energy-harvesting CSNs for wildlife monitoring in large geographical areas, and reveal important insights into the movements and behaviors of migratory animals. In addition to benefiting ecological research, the developed platform is expected to extend the application domain of sensor networks and enable future research applications.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Wireless communication

General Terms

Experimentation

Keywords

Wireless sensor networks, cellular, tracking

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1. INTRODUCTION

The Whooping Crane (*Grus americana*) is one of the most endangered bird species native to North America. As of spring 2011, there are only 575 birds in existence, with no more than 279 individuals in the Aransas-Wood Buffalo Population (AWBP). The AWBP is the only wild migratory population and the source of the nearly 300 birds that are in captivity or have been released in efforts to re-establish the species in Wisconsin, Florida and Louisiana [9]. These birds conduct an annual migration of $4,000$ km (∼2,500 miles) between southern Texas and north-central Canada, during which they travel as much as 950 km/day (∼600 miles/day). Tracking and monitoring the cranes during migration reveals potential causes of mortality, and the impact of changing habitat on bird behaviors. This knowledge is of prime importance to conservation efforts.

Migratory bird tracking has many system, hardware, and software design challenges. The tracking devices must be lightweight and compact so that bird behaviors are not impacted. The extremely high mobility during migration creates severe challenges in maintaining communication links with the birds. Moreover, it is very difficult to recapture a bird once the device is attached. Hence, a tracker must operate reliably under unpredictable environmental conditions during the deployment. The weight and mission duration requirements also impose significant challenges to energy management. Furthermore, due to the lack of existing quantitative measurements on crane behavior, detailed field measurements are needed to establish a baseline for comparison in later experiments. Finally, the endangered status of Whooping Cranes necessitates extensive evaluations of the system on other "proxy" animals prior to deployment on the target species.

Wireless sensor networks (WSNs) have been playing an increasing role in wildlife monitoring [11, 14, 17, 19, 20]. Their light weight, low cost, and communication capabilities are a desirable combination for scientists seeking to analyze animal behavior. However, existing solutions have focused on tracking animals in much smaller geographic areas than the cranes' habitat. The data is not considered time-sensitive, and there is no restriction on the upper bound of the communication delay. In contrast, ecologists studying cranes require the data within 24 hours so that field observations can be made, and causes of death determined. Furthermore, the cranes' migratory paths are unpredictable, which makes it

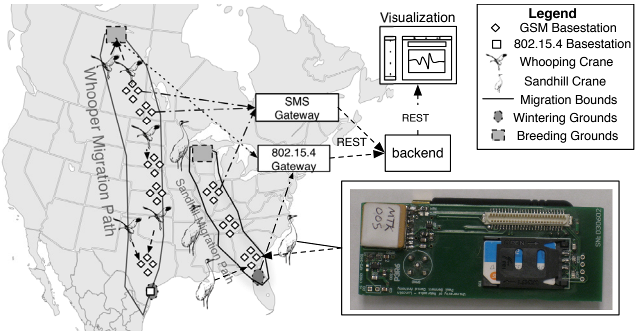


Figure 1: System Overview

impractical to rely on short range, pre-deployed infrastructure. Currently, satellite based trackers are used to provide a high degree of connectivity without relying on fixed terrestrial infrastructure, but have communication delays that exceed 48 hours [31]. These solutions are impractical for many types of wildlife studies which require latencies of less than one day. Finally, existing studies have been characterized by either limited durations and/or frequent maintenance. These limitations prevent existing solutions from being re-used for monitoring birds during migratory periods.

In this paper, we present a multi-modal platform, CraneTracker, for monitoring Whooping Cranes and our experiences from field experiments on wild turkeys and cranes. An overview of the system architecture is shown in Fig. 1, where the migration path of the cranes is highlighted over North America. This figure shows the need for communications connectivity at an extremely large scale. This motivates the use of cellular technology in low-cost sensor applications, where the existing coverage of cellular networks is exploited. In addition, with a second low-power radio, small-scale deployments of ad-hoc networks can still be used to improve communication coverage in key areas, e.g., well-known nesting, breeding, and wintering grounds, and in cases where the ecologists need to acquire information from the field.

Developing software for this new sensing paradigm is complicated by the fault tolerance needed in these systems [6]. The system must cope with defective behavior caused by faulty or physically damaged components. To this end, extensive validation and testing is conducted to eliminate potential faults before the system is deployed. Moreover, the platform must be capable of handling periods of low energy reserves, where the system capabilities are restricted. This is addressed through an energy-aware software and hardware architecture. Finally, a complete monitoring system is developed that incorporates storage and visualization components.

The rest of the paper is organized as follows: First, we present related work in Section 2. Our requirements and the associated challenges for monitoring cranes are described in Section 3. The details of the CraneTracker platform are described in Section 4. The performance of the system is evaluated in Section 5 through component evaluations and field experiments on "proxy" species: wild turkeys, captive Siberian Cranes, and wild Sandhill Cranes. Finally, the paper is concluded in Section 6.

2. RELATED WORK

Whooping Cranes have been the focus of many conservation efforts since the 1930s [9]. However, prior efforts have relied on tracking devices that provide a very limited set of data and require intensive labor. On the other hand, WSNs have successfully been used in wildlife tracking experiments involving other species [11, 14, 17–20]. However, these solutions are limited in terms of mobility, study duration, and communication delays. In this section, we summarize these prior efforts.

2.1 Whooping Crane Tracking

Initial Whooping Crane tracking attempts relied on people maintaining visual contact with the birds. Colored leg bands were placed on the birds to differentiate between them [15]. Ground based spotters would then monitor areas where the birds were known to travel, and keep a record of when and where a bird was seen. The reliance on visual contact meant that birds could not be observed for large portions of their migration.

The lightweight leg bands were eventually augmented by short-range VHF transmitters [16]. Teams of ecologists were then able to follow the birds by using radio direction finding equipment. While this method was an improvement over visual observations, it was still limited in terms of communication range and the effort required to follow a bird.

State-of-the-art tracking methods use GPS receivers and send their findings over satellite communication links. These devices eliminate the need for field researchers to be in close proximity to the cranes. These devices still have several undesirable traits. First, the devices use a 15 cm long antenna that affects the birds' behavior and is a potential failure point. Second, the costs of purchasing and operating the devices are very high. This high cost limits the number that are deployed in the wild. Finally, the quality of the data collected by the devices suffers from the device's limited energy reserves and high latency in reporting the collected data.

2.2 Wildlife Monitoring with Wireless Sensor Networks

Existing wildlife monitoring studies using WSNs can be characterized into two groups based on the network architecture: infrastructure-based and ad-hoc. Data from many of these experiments is stored in a common repository [3].

The first class relies on a carefully deployed infrastructure of nodes to collect information about animals and/or their environment. For example, the burrows of sea birds have been monitored using hierarchically deployed nodes placed in and around burrows [28]. Similarly, WSNs have been used to track and localize badgers using both RFID tags and magneto-induction [11, 19]. These badger tracking experiments utilize fixed infrastructure. Fixed communication and sensing devices are deployed over the badgers' habitat to retrieve the data. These approaches are unsuitable for tracking migratory birds for two reasons. First, it is infeasible to deploy infrastructure over all of the birds' habitat. Second, these approaches do not have an upper bound on the tolerated communication delays, i.e. 24 hours.

As the mobility of the animal increases, infrastructure based solutions become infeasible. Instead, ad-hoc solutions have been employed, where nodes deployed on animals have a higher complexity. ZebraNet utilized GPS receivers and high powered transmitters attached to zebras via collars [14, 18]. The high population density of the zebras allows for multi-hop radio communication in a relatively limited area. In contrast, cranes travel in isolated family groups of two or three, which makes it impractical to solely rely on multi-hop communications. Devices such as UvA [4] and the $CTT-1000$ [1] are capable of using cellular communications or short range radios to track migratory birds. However, these devices do not include both technologies.

The use of GSM modems has been considered for monitoring seals [17, 20]. Similar to the previous work, no strict bounds are considered on when the data is to be delivered. Recently, smartphones with on-board sensors have been utilized for large-scale tracking applications [27]. However, these solutions are heavy and consume too much power to operate unattended for years.

We employ a hybrid architecture for monitoring cranes that relies on global infrastructure (cellular networks) during migration, and short range, ad-hoc networks in breeding and nesting grounds.

2.3 Reliability

In our previous work, we have examined the use of simulation and aspect-oriented programming in testing an older version of the platform [6]. This prior work examined the difficulties in testing systems that are deployed for extended periods in difficult to reproduce environmental conditions. Aspect-oriented programming techniques were adapted to TinyOS for run-time monitoring in simulations. We utilized this technology in this work on a newer platform that has greater capabilities, complexity, and fault-tolerance when compared to the prior system.

Accordingly, a low-cost sensor platform is developed that augments existing sensor network solutions with a cellular modem. To the best of our knowledge, this is the first study that aims to monitor migratory animals in such large areas with a device capable of exploiting both infrastructure and ad-hoc based networking, with a combination of GPS and compass based sensors.

3. BACKGROUND

Tracking and monitoring Whooping Cranes during migration is essential for conservation efforts since the majority of mortalities occur during this period. Moreover, continuous monitoring of cranes is important to reveal the impacts of changing habitat on bird behaviors. Characterizing crane behaviors can lead to accurate estimations of a bird's energy needs. These estimates can reveal relationships between habitat usage and population. In this section, we present the requirements and the challenges encountered for monitoring cranes.

3.1 Requirements

Working with ecologists with experience in maintaining the crane population, we developed goals and requirements for a new tracker. The key requirements are briefly listed. A detailed description and rationale for them will then be presented.

- Weight: < 120 grams
- GPS: 2 samples per day
- Location Accuracy: < 10m desired, < 25m acceptable
- Compass: 0.5Hz sampling rate
- Communication Latency: < 24 hours

Migration tracking: During migration, the birds are highly mobile and highly unpredictable in terms of their paths and nightly roost sites. Timely location information can be used to locate the cranes' roosts during migration and can create insights into how the birds choose these intermediate stops. Knowledge of a bird's location can also be used to determine whether or not it has perished, and whether to use field personnel to ascertain a cause of death.

To support this research, at least one location must be provided by the GPS during the day, and one during the night. It is desirable, but not necessary, for the GPS location to be accurate with 10 meters of the true position so detailed habitat monitoring can be conducted. GPS measurements that are within 25 meters of the true position are desired for tracking the birds during migration and determining mobility patterns. Such insights into the birds' travel habits are of great importance to ecologists because they can help measure the effects of habitat changes and other human development on the birds' behavior and migration patterns. Gaining knowledge into the real world performance of the GPS solution will enable more efficient power management and data sampling algorithms.

Reduced latency: Many open research questions regarding the cranes, such as when and how they die during migration, require timely data to be sent during migrations. If information on a crane's location and behavior is delayed, it may be impossible to locate the crane in the wild to conduct field observations, or if necessary, recover the corpse. Existing, state of the art, satellite based solutions frequently have communication delays exceeding 48 hours [31]. The requirements for this project specify an ideal delay requirement of less than 24 hours during migration.

Bird movement characterization: Collecting information on how the cranes move is another important step in ensuring their survival. Their flight behavior is not well quantified, because the existing data comes from qualitative and opportunistic visual observations. While on the ground, information about their movements such as foraging, roosting, and preening help characterize their energy usage and can lead to the development of time-energy budgets for the cranes. A greater understanding of their behavior is important because it may expose changes in the birds' behavior caused by climate or habitat change. Movement data can be used to determine whether or not a bird is alive. If the bird is dead, then field personnel can retrieve the corpse for further study. To collect behavioral data, the compass must be sampled faster than 0.5Hz. The studies presented in this paper sampled the compass at 1Hz for 10 seconds, with 4 hours in between sampling periods.

Long-term operation: Gathering statistically valid movement and behavior data from migratory birds requires multi-year operation, during which an individual can be observed for several migration cycles. To prevent any impact on the behavior, it is not desirable to re-capture a crane after a tracker has been mounted. Consequently, the harnesses are designed to eventually wear out and detach from the birds within several years. During the time a tracker is on a bird, it is expected to function properly without outside intervention.

Flexible operation: Multi-year and continuous monitoring of the same bird can reveal important insights into behavior over its lifetime. There are very few prior studies of this type, which leads to a lack of baseline data. Thus, at this point, the best data collection policy for ecologists is to get all the raw data in order to establish a baseline for future experiments. Further complicating data collection is the wide variety of environmental conditions the trackers will encounter. This makes it hard to *optimize* system operation since input space is largely unknown. The tracker should be flexible, so that its operation can be revised based on experimental results. This allows for more advanced filtering and data collection schemes to be implemented in the future.

Backpack Mounting: State-of-the-art Whooping Crane tracking systems use a leg-band design. There are several drawbacks with such a design. First, the added weight can unbalance the bird, and add drag, which makes it more difficult to fly. More importantly, there has been anecdotal evidence that a leg-band can adversely affect copulation which is unacceptable for conservation efforts. Instead, a backpack mounting design is employed, which is evaluated with Siberian and Sandhill Cranes.

3.2 Challenges

Monitoring migratory birds during migration faces several challenges, some of which are common to wildlife monitoring platforms (e.g., weight limits) and some of which are more specific to cranes (e.g., extreme mobility during migration). In the following, we summarize these challenges.

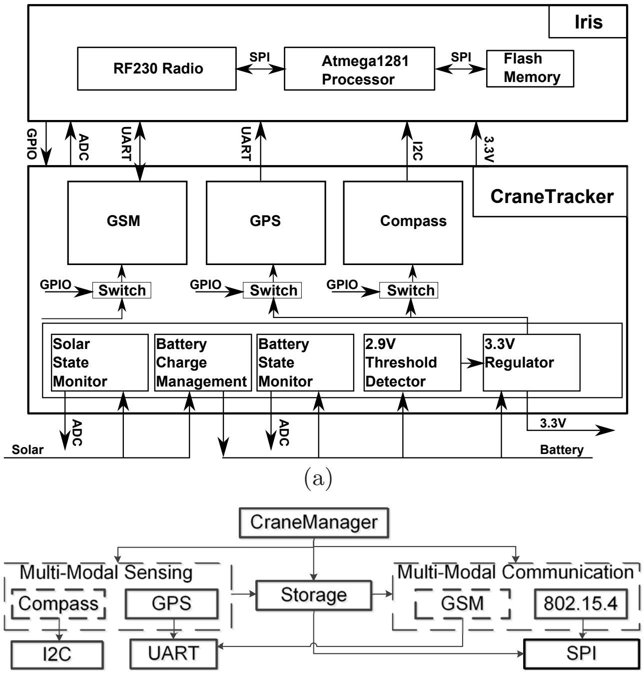
Weight and Size Restrictions: Using guidelines developed for other birds, a device and all supporting equipment must weigh less than 2% of a crane's bodyweight [30]. An average crane weighs 6kg. The equipment used to attach the device to the cranes weighs approximately 10 grams, so the device itself must weigh less than 110 grams.

These requirements are very restrictive when compared to many efforts. For example, the collars used to track zebras in ZebraNet [14] weigh over 1.1kg. A tracking experiment with badgers faced weight requirements similar to cranes [19] (105g), but the mission duration was much shorter (3 months) and the trackers used a lower power sensor. For cranes, ecologists have recommended that the tracker be no larger than 19.5cm long, 2.5cm tall, and 6.5cm wide. This allows the tracker to be attached to the bird as a backpack without affecting the bird. The weight and size restrictions place a significant restriction on the type of battery to be included and makes energy harvesting a necessity for the system.

Mobility: Whooping Cranes travel as much as 950 km per day, and can move 4,000 km over the course of migration. Along with their rapid movement, the birds travel as family groups instead of in large flocks. Hence, it is extremely difficult to predict flight paths, stopover points, and flight durations during migration. This unpredictability makes maintaining communication links with the birds a major challenge. Placing ad-hoc infrastructure along migration flyways is a near impossibility. On the other hand, cranes use the same region for breeding and wintering for years. These locations are ideal spots for ad-hoc communication.

Unattended Operation: The required mission duration is 5 to 7 years, which is significantly longer than existing tracking efforts [19, 20], which run for weeks or months. Since trackers cannot be accessed once harnessed to a wild bird, the system should be self-sustainable in terms of energy resources during this time. In addition, the software should operate without any errors despite the device being exposed to many unknown conditions. This makes it extremely desirable for the device to have a runtime that lasts for multiple migration periods. Moreover, the software must be able to cope with low voltage conditions or physical damage.

Unknown Behaviors: The lack of quantitative measurements on crane behavior makes the design of a sensing scheme highly challenging. Lacking solid baseline data makes it difficult to develop effective sensing or communication routines to record the relevant aspects of crane behavior. Developing software that can handle these conditions is a difficult task because not all possible environmental conditions can be recreated in a controlled environment. The long term nature of wildlife tracking means that some software faults may manifest very slowly and be difficult to expose prior to deployment.



(a)

(b)

Figure 2: CraneTracker (a) hardware and (b) software architectures.

Endangered Status: Whooping Cranes are a federally endangered species. Hence, any potential new technology to study them is highly scrutinized. The platforms developed for studying Whooping Cranes must first be tested on other "proxy" species before being accepted by the U. S. Fish and Wildlife Services. Once the platform has been accepted, it can be used for monitoring the AWBP Whooping Cranes.

4. CRANE TRACKER

To address the challenges discussed in Section 3.2, and achieve the requirements listed in Section 3.1, a crane monitoring system is developed. The system consists of two major components: (1) The CraneTracker that is attached to the cranes and monitors their movement throughout the continent and (2) the back-end components that are used to store, analyze, and visualize the collected data. Next, we describe in detail the CraneTracker platform, system development, and evaluation tools. A more detailed description of these components is available in [7].

4.1 Overview

CraneTracker consists of a family of integrated hardware software components, which are illustrated in Figs. 2(a) and 2(b), respectively. The hardware architecture consists of an Iris mote and a custom sensor board with a rich set of sensors, modem, and power control circuitry. The software architecture was built on top of TinyOS and includes sensor and communication drivers, and storage, power, and overall system management. This system overcomes the challenges enumerated in Section 3 through:

- Weight and Size Restrictions: careful selection and integration of hardware components into the custom board (Sections 4.2 and 4.3), and a custom built enclosure (Section 4.6).

- Mobility: integrated multi-modal communications which includes an Iris mote with an 802.15.4 compatible transceiver and a GSM modem, and support to handle holes in coverage through temporary data storage (Sections 4.2 and 4.5).

- Unattended operation: integrated energy harvesting through a solar panel, and power control sub-system to maximize data capture and battery recharge opportunities (Sections 4.4 and 4.5)

- Unknown behaviors: integrated multi-sensing capabilities with GPS, GSM, 3D acceleration, magnetometer, and temperature sensors delivering data to the scientists on the fly (Sections 4.3 and 4.5)

- Endangered status: incremental deployments on turkeys, Siberian Cranes, and Sandhill Cranes (Sections 5.2, 5.3 and 5.4).

4.2 Multi-Modal Communication

As discussed in Section 2, short-range multi-hop communication schemes are insufficient for maintaining connectivity in a highly mobile sensor network. On the other hand, well-known breeding and wintering grounds provide an opportunity for establishing ad-hoc communication with the cranes. Additionally, ecologists seek time critical information while in the field. This unique requirement calls for a multi-modal communication scheme.

For a long-range communication solution, two alternatives exist: satellite and cellular communication. Satellite technology was avoided because of the drawbacks listed in Section 2.1. Cellular communication is desirable because the necessary infrastructure is already deployed throughout the migration path. The experiments also reveal that this infrastructure enables the trackers to communicate *in flight*. Moreover, the operating cost is significantly lower than that of satellite systems.

Two main technologies exist when choosing the cellular device: CDMA and GSM. GSM technology is used for this project because its widespread international adoption will enable future experiments in a wide variety of locations. A GE865 cellular module from Telit is used for the GSM functionality [29]. This module has several appealing features for this project. First, it only weighs 3.5g. Second, it uses UART lines to interface to a microcontroller. This interface is very common in microcontrollers, and is simple to implement. Third, it supports domestic and international GSM bands, which means it can be deployed to many places in the world. Lastly, it is controlled through standard AT commands [5], which allows future versions of the platform to use alternative modules and technologies.

The GSM module requires careful power supply design. While the rest of the platform components operate at 3.3V, the GSM has a normal operating voltage of 3.4V to 4.2V [29]. According to the datasheet, the module consumes an average of 240mA during a voice call, and up to 420mA if the GPRS functionality is used. Testing on the CraneTracker showed the module used an average of 64mA while sending a text message. The current consumption of the GSM while associating with the cellular tower and sending repeated SMS messages is shown in Fig. 3. Although not shown in Fig. 3, under certain circumstances, the peak power demand of the GSM can reach 2A.

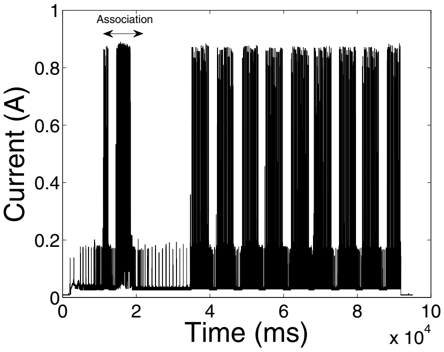


Figure 3: GSM current while sending SMS

To communicate between the Iris mote and the GSM module, a GSM driver is developed for TinyOS [2]. Using standard AT commands, a subset of the commands needed to establish communication with the cellular network and send an SMS is implemented. Additional information, such as the cellular tower used for the connection, is fetched through the interface as well. By tracking which cellular towers the system associates with, the GSM module also provides coarse grain localization.

Despite its extensive coverage, cellular infrastructure is focused on covering human population needs. Given the remote areas the cranes travel to, cellular coverage can occasionally be missing. Occasional holes in coverage during migration can be compensated for with a storage mechanism as will be explained in Section 4.5. However, in breeding and wintering locations, cranes generally use the same locations over several years. If cellular coverage is lacking at this particular location, long-term storage may not be sufficient to store all of the recorded information. Since the locations of breeding and wintering grounds are well known, it is feasible to deploy short-range base stations at these locations. Thus, the CraneTracker utilizes the 802.15.4 compatible radio located on the Iris mote. The radio utilizes single-hop communications with the default protocols implemented by Memsic [21] in MoteWorks. This radio will be used in future experiments once the mobility patterns and family dynamics of the cranes are better explored. The resulting network architecture is shown in Fig. 1, where the two modes of communication are illustrated.

4.3 Multi-modal Sensing

Sensing components were selected to provide information about the bird, the environment, and the system. The sensing requirements specify position information, movement information, ambient solar power, temperature, and battery voltage.

The GPS sensor is a PA6B module manufactured by GlobalTop Technologies [12]. The selection of this receiver is based on multiple factors including power consumption, chip weight, antenna weight, size, channels, sensitivity, position accuracy, durability and time-to-first-fix (TTFF). The selected GPS module has a quick TTFF (34s cold start), low energy consumption (43mA), and small size (16mm x 16mm x 6mm) [12]. In addition to these characteristics, the module features an integrated patch antenna, which makes it compact and easy to integrate into the tracker. The GPS interfaces to the host microcontroller through UART lines. The NMEA 0183 protocol is used to communicate information such as the location, altitude, speed, and course over ground of the bird. This data is then used to track where the bird has traveled, where it is heading, and whether or not the bird is still alive.

To characterize the bird movements and behaviors an HMC6343 solid-state compass, which includes a three dimensional accelerometer and magnetometer, and temperature sensor in a single package, is selected [13]. The solid-state compass provides a yaw accuracy of 2^o and pitch and roll accuracy of $\pm 1^o$ between 0^o-15^o and a $\pm 2^o$ accuracy between 15^o-60^o. The compass communicates this information over the I2C interface. The default TinyOS I2C implementation was replaced with an interrupt-driven component to correct timing problems between the compass and microcontroller. To provide baseline data of crane movements, our strategy has been to obtain raw data from the cranes for this work.

Environmental data is collected through the temperature sensor in the compass and through the solar panel. To infer the intensity of ambient light through the solar panel, the voltage and current are recorded from the panel. In addition to bird-specific and environmental data, information about the system performance is also desired. To this end, the solar panel and battery are monitored as a part of the power control component which is described next.

4.4 Energy Harvesting and Power Control

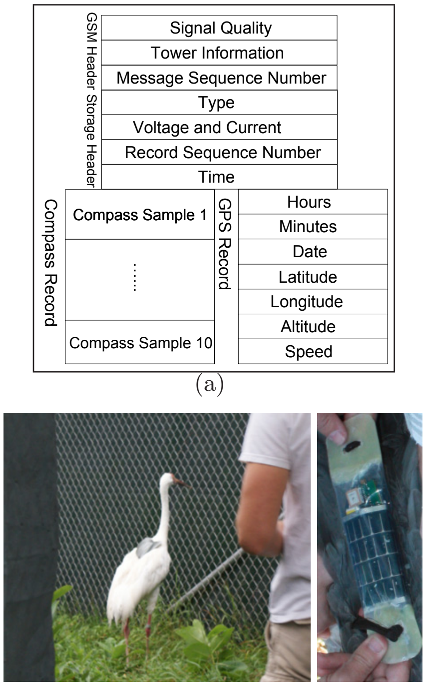
To maximize the lifetime of the device, a flexible solar panel from PowerFilm [26] is used to recharge a lithium polymer battery. The solar panel specification states it is capable of providing 50mA at 4.8V. A lithium polymer battery is used because its high energy density minimizes the weight of the device, while allowing it to run for extended periods when solar energy is not available. The use of a lithium polymer battery complicates the power supply of the system, as it must be recharged using specific routines to maximize the battery lifetime and to avoid damaging the battery. Over- and under-discharging the battery must also be avoided, as this will also damage the battery.

An overview of the circuit that implements these operations is shown in Fig. 2(a). The power provided by the solar panel is used as the input to a charge management circuit [24]. The voltage and current supplied by the solar panel is monitored and logged by the mote as well. The output from the charge management circuit is used to charge the battery. The battery voltage and discharge current are also monitored by the microcontroller to profile the energy consumption of the device and enable power-aware operation. The battery state is monitored by a dedicated IC [25], which enables a 3.3V linear regulator [22] when the battery is sufficiently charged. This linear regulator is used to power the components which are unable to cope with the 4.2V that the battery can potentially supply. The power to the individual components is controlled by an IC switch, which provides a low-complexity method of disabling the devices [23].

The separation of software from system control enables the system to recover from unforeseen software errors. The usefulness of this approach is empirically supported through the deployments, where the system is able to recover from an unknown error state, as will be discussed in Section 5.4.

4.5 Data Management

The 512 kB of flash memory on the Iris is used to store information before being transmitted to a base station. Data is organized into sensor records, as shown in Fig. 4(a). The records stored in flash are divided into compass and GPS records that are prefixed with a common header. The stored data is organized into a FIFO circular queue that can hold up to 16,912 records. In the event that the queue fills without data being transmitted, the oldest data in the system is overwritten first. This behavior is motivated by the expected communication patterns. The data collected during migration periods is of greater interest than the data that is collected during wintering and roosting periods. However, the wintering and roosting periods will probably experience the longest periods of communication silence, due to the lack of cellular coverage and difficulties in placing short range base stations near the birds. Thus, during these times, the buffer may fill with less interesting data, that will be overwritten as part of the FIFO process.



(a)

(b) (c)

Figure 4: (a) Packet format (b) CraneTracker enclosure designs (b) and (c).

When the data is transmitted, a second header is prepended to the data that contains information for detecting dropped packets and logging information on the cellular connectivity. The data is transmitted according to the FIFO protocol, where the oldest data is transmitted first. This greatly simplifies the implementation of the storage mechanism. However, in some cases, this behavior can be undesirable, as during migration it is more interesting to see the recent locations of the birds. Investigating trade-offs in storage and data retrieval policies, e.g. LIFO, is left as a future work once sufficient data about tracker behavior is collected.

As illustrated in Fig. 2(b), at the highest level of the system, a software manager is implemented that schedules when sensors and communication devices are used. The manager is power-aware and monitors the battery voltage before activating a component. Consequently, the system avoids wasting power by using components that will not be able to operate effectively. This improves the chances that future tasks will have enough power to run.

4.6 Enclosure Design

To fulfill the durability and environmental protection requirements, several harness and enclosure designs were evaluated.

Based on the feedback from ecologists, a backpack approach is used. This allows the tracker to be mounted near a bird's center of gravity, and minimize the effect on copulation. In addition, a backpack design has potential benefits to system design since exposure to the sun and movement monitoring accuracy increases when compared to a leg band. Three designs were used in field tests including a hard plastic enclosure, a pouch, and flexible plastic tubing.

The turkey tests used hard plastic enclosures, with the solar panel attached to the outside. These are too bulky for the cranes. The second design is used in short-term field experiments with captive cranes (Fig. 4(b)), where the tracker is retrieved within a day. The pouches were made from heat-sealable Oxford cloth that is waterproof and easy to prepare.

The final enclosure design is inspired by an outdated VHF transmitter package, which operated for three years on a crane, that used heatshrink tubing. A transparent heat shrink is used to enclose all components and still allow for solar recharging. A high strength plastic welder is used to bond the ends of the tubing. These enclosures are tested by submerging them in water, freezing, physical stress, and exposure to weather. A functioning mote is kept inside the enclosure during the tests to make sure it is unharmed. This plastic tubing approach is extremely durable, and passes all of these tests. The final unit is shown in Fig. 4(b) and Fig. 4(c) on a Sandhill Crane and is used in on-going alpha experiments that will be explained in Section 5.4.

4.7 Fault Detection and Tolerance

To maximize the chance of a mission's success, the system must be fault tolerant. Additionally, the system software should undergo thorough testing and verification. In our previous work, we presented work on testing the system software on an earlier platform [6]. We utilized these techniques in the current design. Next, we will present the new fault-tolerant features of the updated platform.

The first area of fault tolerance is in the communication scheme. The combination of GSM and short-range radio enables the tracker to continuing operating when one method is damaged or unable to communicate. Second, the GPS and compass can redundantly sense some of the information about the cranes, such as whether they are alive or dead. Finally, the hardware provides fault tolerance for the software. In cases where a software fault leaves the system in a high energy consumption state, the hardware is capable of removing power and rebooting the system after too much energy has been consumed.

5. EVALUATION AND DISCUSSION

The CraneTracker has been extensively evaluated via component evaluations, controlled system experiments and ongoing field experiments. Through component evaluations, the individual hardware components are characterized and the associated software components are validated. Controlled system experiments provide insight to the operation of the whole system and allows us to tailor the operation parameters.

Due to the endangered status of Whooping Cranes, the platform has been tested on "proxy" species that share similar habitat or similar characteristics with the Whooping Cranes. Preliminary platforms were evaluated on Wild Turkeys (*Meleagris gallopavo*), which share habitat with the cranes and provide a convenient method of testing many aspects of the platform because of their abundant population and low mobility. These experiments also allowed us to evaluate the latency of the cellular interface in the wild. Once successful, system evaluations have been conducted with captive Siberian Cranes (*Grus leucogeranus*), a close cousin of Whooping Cranes. These experiments were conducted at the International Crane Foundation (ICF), in Baraboo, Wisconsin, where the captive cranes are held in pens. The backpack design, ad-hoc communication, and the compass monitoring capabilities are tested on these cranes with short-term experiments. The final experiments consist of alpha deployments with wild Sandhill Cranes (*Grus canadensis*) - another abundant cousin of Whooping Cranes - where the system is fully tested in a realistic environment. At the time of this writing, five trackers have been placed on wild Sandhill Cranes. Two of the birds have completed migrations from Wisconsin to Indiana and Florida.

5.1 Preliminary Evaluations

Characterization of performance at the component level was performed to validate the system design. In Fig. 5(a), a high level view of the system's power consumption is shown. The details of this analysis are not discussed due to space limitations. As can be observed, power consumption profile of CraneTracker is fundamentally different than traditional WSNs, where the energy consumption for sensors is generally neglected. In contrast, the compass on the CraneTracker uses approximately the same amount of power as the microcontroller, and the GPS uses significantly more. Furthermore, the GSM consumes by far the most power. The power usage of the different components calls for energy-aware management of all the parts of the system.

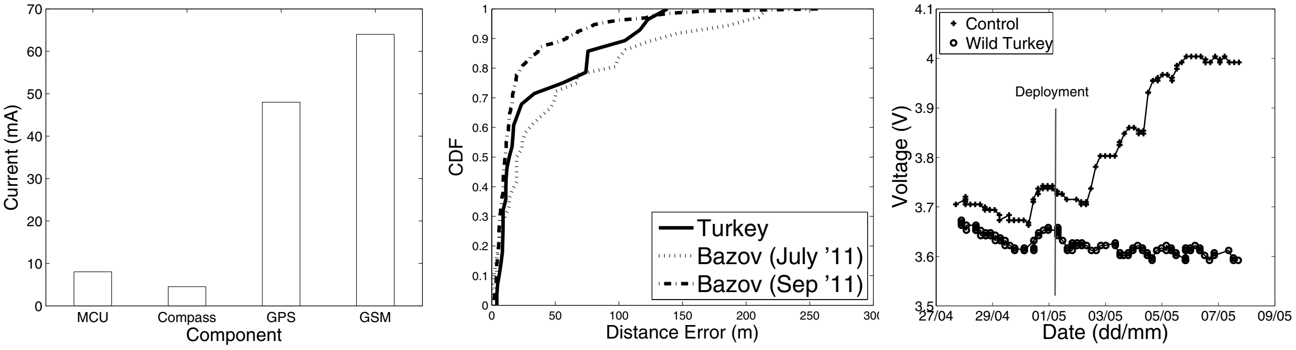
Initial system-wide evaluations were performed by driving approximately 160km through an area commonly used by the Whooping Cranes during their migration. These experiments provide insights into the communication delays of the system and the accuracy of the measured results. The communication delay over the duration of the experiment is found to be only 6.07 minutes ($\sigma = 1.53$ min). As shown in Section 5.4, this latency is optimistic since well covered highways are used, but shows significant improvements compared to the 48 hour satellite tracker delays.

The experiment also reveals the localization accuracy of GSM. Over the course of 160 km, 18 base stations were seen and each base station provided an estimate of the mote's location. Using the GPS sensor as a baseline, it is observed that the error has a relatively large variance, where 50% of the error is less than 4 km and the maximum error is bounded by 14 km, which is useful for coarse localization in case of GPS failures. The satisfactory results with controlled experiments motivated the evaluation of the system on animals as explained next.

5.2 Field Experiments with Wild Turkeys

Field observations reveal that 2/3 of the Whooping Cranes' migration is spent foraging and roosting in habitat very similar to wild turkeys'. To evaluate the tracking accuracy, communication performance, power consumption, and recharge performance in a limited area, field experiments were performed with wild turkeys. These initial experiments demonstrated the viability of cellular-based sensing for remote and time critical wild bird monitoring.

In the experiments, two sets of data are used: (1) *Turkey tracker:* A tracker is attached to the back of a captured



(a) (b) (c)

Figure 5: (a) Power consumption of platform components, (b) CDF of GPS error, (c) Battery voltage of control and turkey tracker.

hen and the hen is released for monitoring for a week. (2) *Control:* A stationary control mote is placed in the open within 1 km of the hen's habitat. This mote consists of the same hardware and software as attached to the captured turkey.

The collected data includes 480 SMS messages, 105 GPS, and 9,170 compass-related data over a period of 10 days. The system provides 100% reliability, where the turkey tracker sent SMS messages every 4 hours except for 9 cases, where the missing SMS was received in the following communication window, i.e., with a 4-hour delay.

System Evaluation: In Fig. 5(b) the CDF of the GPS location error for the experimental evaluations is shown. For the turkey experiment, the accuracy is evaluated by placing a tracker at a known position, and comparing the reported location to the known location. A large portion of this error is caused by operating mode of the GPS. In this trial, the GPS was turned off immediately after it acquired a fix in order to save power. This is insufficient time for the error in the GPS receiver to converge to its lower bound. This truncation contributes to the GPS error, along with the non-ideal environmental conditions.

The position of the wild turkey was acquired every 4 hours during the 10 day release, where the turkey was successfully monitored in a 2km x 1km area using the cellular communication capabilities of the tracker. The location data is divided into sets based on the time of day (night, early morning, morning, early afternoon, and afternoon) as illustrated in Fig. 6. The roosting location of the turkey can be clearly observed by the congregated fixes during night, early morning, and afternoon (see zoomed-in graph). It is observed that most of the movement occurred during early morning and afternoon when the bird was feeding with the bird moving as far as 1 km over a 4 hour period.

In Fig. 5(c), the recharge performance is depicted, where the deployment time is indicated by a vertical line. The control mote clearly outperforms the turkey tracker because it was placed directly under the sun. Although self-sustaining, the turkey tracker results in a lower recharge rate due to the woodland habitat, where the turkey spends most of its time. Moreover, Fig. 6 yields evidence that the wild turkey was in woodland coverage during mid-day, when the sun exposure is at its peak. Both data sets provide insight into how the CraneTracker will perform during a crane migration. The control set represents conditions similar to flight, when cranes are known to migrate up to 8.8 hours a day. This allows the device with sufficient time to recharge under direct sunlight. In contrast, the turkey data provides a lower bound on the energy regeneration performance on the ground.

Ecological Observations: Even though it was not our primary goal, the turkey tracker data also provides important insight into turkey behavior. Turkeys spend up to 95% of the day feeding and are able to move at a rate of 200 m/hr during feeding periods [10]. The collected data supports these conjectures. The locations during the night and afternoon correspond to the hen's brooding and nesting area. The other GPS positions are probable feeding areas, in which the turkey is found in the rest of the day. GPS positions from one day are also connected in Fig. 6, where observed movements of up to 1 km over a 4 hour period fall closely into the 200 m/hr observations [10]. The close agreement of the collected data with the observed behaviors of wild turkeys provide an additional validation to the platform operation.

5.3 Captive Siberian Crane Experiments

To evaluate the performance on a real crane in a semi-controlled environment, the CraneTracker was tested in July 2011 with three captive Siberian Cranes: A. Wright, Bazov, and Hagrid, held in separate pens of 10m x 10m. A soft water-resistant pouch was used to harness the instruments to the captured Siberian Cranes as shown in Fig. 4(b) for a day. During the experiments, GPS and GSM communication capabilities as well as compass accuracy were tested. The ecologists also observed the impacts of backpack harness technique on the cranes.

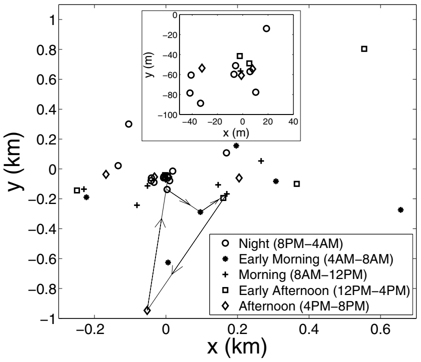
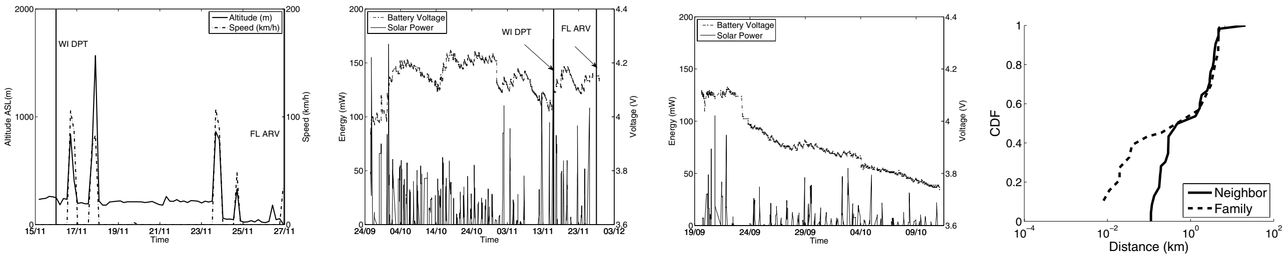


Figure 6: Turkey positions (lines connect consecutive fixes for one day).



(a) (b) (c) (d)

Figure 7: (a) SH-Chick altitude and speed. Solar power and battery voltage for (b) SH-Chick and (c) JB-Female. (d) Distance between SH-Chick and family and neighbors.

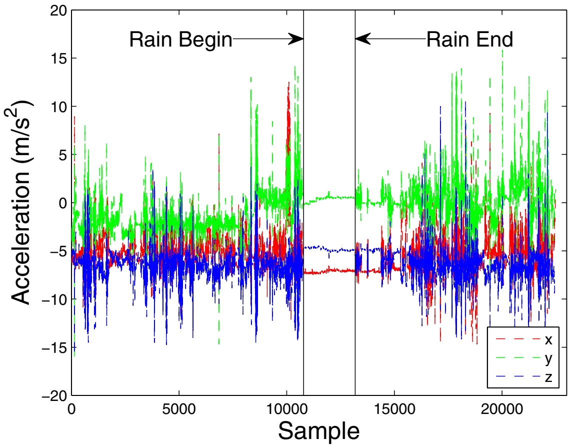


Figure 8: Three-axis acceleration readings from a Siberian Crane.

System Evaluation: With A. Wright and Bazov, the tracker was programmed with a 4 hour duty cycle. During each cycle an attempt was made to acquire a GPS fix and the compass was sampled. After the sensors were sampled, an attempt was made to send the data using the GSM. A. Wright incapacitated the device immediately after deployment by hitting a fence.

With Bazov, over 27 hours, a GPS fix ratio of 97% was achieved out of 135 attempts. Fig. 5(b) shows the CDF of the GPS error for Bazov, assuming that the bird was located in the center of the pen. The results show that 58% of the errors are less than 25m. To improve the accuracy, the GPS sampling scheme is updated so that at every attempt, 10 GPS fixes are acquired before firing a success event. With this update, the experiments were repeated in September 2011 with Bazov in the same pen. As shown in Fig. 5(b), this update improves the accuracy of GPS so that 81% of the errors are less than 25m. In this experiment, a large portion of the errors are due to the bird moving around the cage, and not staying in the center (±7m). These movements contribute to the errors in the figure. The remainder of the errors are due to environmental factors, and the GPS not operating for an extended time period to minimize the energy consumption. The distribution of errors satisfied the ecologists working on the project, and the quality of data met their needs.

To evaluate the compass accuracy on a crane, Hagrid was monitored by a closed-circuit camera system and compass readings were collected at a high rate of 10Hz for 30 sec every 3 minutes using the Iris mote's radio. Data from the compass was collected over 4 hours and 21,882 records were received. A part of the results is shown in Fig. 8, where the three dimensions of acceleration are shown before, during, and after a heavy rain. During the rain, the crane was observed to stand still, which can be observed on the marked area of the graph. Moreover, during the experiment, the researcher logging data was able to determine movements without actually seeing the bird. The movements were confirmed by another researcher observing the crane through a video camera. Such strong correlation between accelerometer readings and crane behaviors motivate the utility of the compass for developing and validating energetics models for cranes [8] and further study on the collected compass data is left for future work.

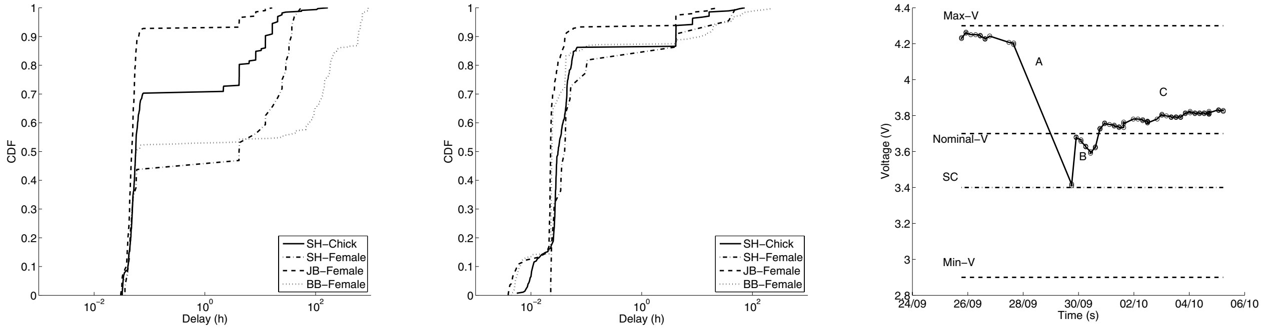
Lessons Learned: During the experiments at the site, heading, pitch, and roll were inconsistent even though component tests were successful in other locations. This erroneous behavior was confirmed with all compass units available as well as an alternate inertial measurement unit and a smartphone. Unfortunately, the compound sits on a dense magnetic field due to a moraine that affects sensitive magnetic electronic readings. This behavior highlights the significant fluctuations sensors may experience during a long migration that encompasses several states.

5.4 Wild Sandhill Crane Deployments

The wildlife experiments with CraneTracker have been conducted with alpha deployments on five Sandhill Cranes. The cranes are captured in the wild by trained professionals and released to the wild after necessary measurements are taken and the trackers are attached. Five cranes from three families have participated in the experiments. The cranes are designated JB-Male and JB-Female; SH-Female and SH-Chick; and BB-Female. The two letter prefix identifies the crane's family, and the suffix is the crane's gender. Relevant information about the trackers is summarized in Table 1. The trackers will be left on the cranes for a year to observe their migration.

The software follows a schedule such that the system wakes up, collects a GPS fix, gathers 10 compass samples over 10 seconds, and then attempts to communicate with both the 802.15.4 radio and the GSM, and sleeps for 4 hours 5 minutes. The GPS fix is recorded after acquiring 10 valid fixes, which is found to improve the location accuracy as discussed in Section 5.3. To prevent excessive energy consumption, the GPS is turned off if a fix was not acquired within 5 minutes. The 4-hour 5 minute sampling interval and 10-second compass sampling duration was recommended by the ecologists. The sampling interval was selected so that the sampling times shift in time and in long-term, information from each time of day is collected.

System Evaluation: Fig. 10 shows the migration



(a) (b) (c)

Figure 9: (a) CDF of delay (comm.+queue), (b) CDF of communication delay, (c) Low-voltage recovery.

Table 1: Experiment Summary

Name	Exp. Duration (days)	# SMS	# Fixes	Distance Traveled (km)	Comments
JB-Male	13	0	0	-	Failed to recharge
JB-Female	41	2,795	208	20	Unknown
SH-Female	29	525	468	4.3	Fell off
SH-Chick	66	1,890	330	1,725	Operational
BB-Female	121	2,213	468	603	Operational

paths taken by SH-Chick and BB-Female during the fall of 2011. SH-Chick completed the migration to the southern habitat in Florida, while BB-Female chose to halt the migration in Indiana. This figure demonstrates the unpredictability of the cranes, and the extreme geographic distances the devices operate over.

Experimental results from the birds confirm the viability of using the cellular network for monitoring during migration. During the migration, SH-Chick recorded 330 total GPS locations. Of these 330 locations, the bird's velocity indicated that in 12 of them it was flying. During these flying periods, SH-Chick communicated 10 times. These results show that the tracker is capable of maintaining a high degree of connectivity during all phases of the bird's life cycle.

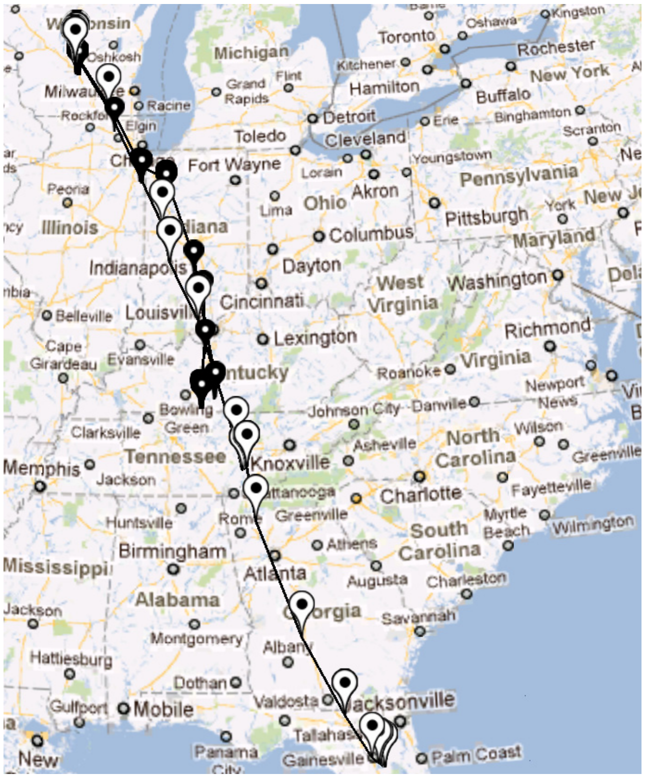


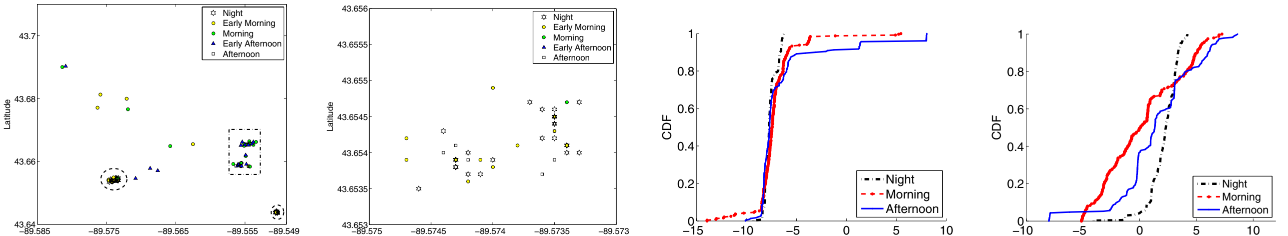
Figure 10: Migration paths of SH-Chick (white marker) and BB-Female (black marker)

Fig. 7(a) shows the altitude and speed of SH-Chick over the course of the migration. Naturally, there is a strong correlation between the speed and altitude of the bird, as the cranes are capable of flying much faster than walking. This figure also illustrates the difficulty in monitoring the cranes. They are capable of achieving high speeds while in the air, and flight periods comprise a surprisingly small portion of the actual migration process.

In Fig. 7(b) and Fig. 7(c), the battery voltage and the solar power collected by the monitoring circuit is shown for JB-Female and SH-Chick. These figures show that there is a close correlation between the monitored solar power and the battery recharge rate and solar power levels higher than 20mW leads to a recharge. Below this power level, the recharge circuitry is unable to utilize the power to recharge the battery. Accordingly, the readings can be used for adaptive operations, where the battery levels are predicted based on solar power.

The differences in recharging behavior between different birds is due to their location. In the breeding grounds, where the cranes spend most of their time, the birds are often in vegetation. This vegetation can obscure the solar panel. It can be observed that JB-Female has a lower recharge rate but the battery levels are above the critical threshold of 3.65V. As shown in Fig. 7(b), during migration (16/11-28/11), the device is capable of recharging the battery in a matter of days.

The power control circuit prevents the battery from draining below a minimum energy level, in order to prevent damage to the battery. This results in a sustainable albeit potentially *intermittent* operation. The collected information will provide insight into suitable sampling ranges and adaptive operation to reach a *continuous* sustainable operation.



(a) (b) (c) (d)

Figure 11: (a) GPS locations of JB-Female over 24 days, overall fixes (b)and zoomed circle cluster, Acceleration for SH-Chick for (c) z-axis and (d) x-axis.

The distance between the SH-Chick and SH-Female, and SH-Chick and JB-Male, is shown in Fig. 7(d). The close proximity of the chick and its mother raises the possibility of creating ad-hoc networks with short range radios in the future. Such networks could enable better data collection and experimentation through improved sensor coordination between family members. Moreover, these networks could improve the data delivery reliability, and possibly improve the lifetime of the motes.

The delay performance of the tracker is shown in Fig. 9(a), where the CDF of the delay is shown for JB-Female, SH-Chick, SH-Female, and BB-Female. The delay is defined as the time between a sensor sample is taken and it is received by the backend. Fig. 9(a) demonstrates that for JB-Female and SH-Chick, more than 98% of the delay is less than 24 hours. For BB-Female and SH-Female, the 24-hour quantiles are 55% and 72%. Most of the delay above 24-hours is due to the FIFO queue used in the system for the initial deployments. A long missed communication window leads to queue build up, which affects the delay even if the tracker can communicate afterwards. In Fig. 9(b), the delay due to *only* missed communication windows are shown. This corresponds to the delay if a LIFO queue were to be used in the system. It can be observed that for all the birds, more than 94% of the delay is less than 24 hours, which justify the use of GSM communication technology to meet the requirements of ecologists and motivate our future work for more efficient queueing models.

Lessons Learned: In two occasions, JB-Male and SH-Female, the system failed. The first tracker was harnessed to JB-Male in July-August 2011 and transmitted information for 13 days, during which all GSM packets were received within 8.3 hours. However, the GPS was unable to acquire a valid fix, and the battery voltage steadily decreased without showing any signs of recharging. While it was impossible to recover the device from the crane, it is likely that the solar panel became detached and slid over the GPS antenna. Based on the JB-Male experiment results, the mechanical design and the enclosure were improved to prevent movement and the second set of experiments were performed in Sept. 2011 with four additional cranes.

In the case of SH-Female, the tracker exhibits irregular behavior. The battery voltage for the bird is shown in Fig. 9(c). The results show that the system was stuck in an unknown error state, and recovered from this state after battery depletion. At time A in Fig. 9(c), the battery voltage was at full capacity and at time B, the tracker sent a message with a minimum allowed voltage and a system reset notification. Then, the system returned back to a steady state, after a small amount of recharge time. This behavior validates the effectiveness of the power control circuit but results in an intermittent communication with the backend. It is postulated that the failure was due to the GPS component since no valid fixes have been received since the failure. The GSM header still provides coarse location information so it was decided to leave the tracker on the crane and further observe the harness impacts and the system behavior. However, field observations soon after revealed the tracking device was no longer attached. The results highlight the increased connectivity provided by the GSM interface in the wild while revealing practical problems that the tracker will endure during operation.

Ecological Observations: The 4-hour sampling interval and the staggered operation provides insight into the daily movements of cranes. In Figs. 11(a) and 11(b), the locations of JB-Female are shown for different times of day over 24 days. It can be observed that all the night and most of afternoon data correspond to two distinct roosting locations as indicated by circles. The roosting locations in this area have generally been known by the ecologists but the collected information revealed individual information about where each specific crane roosted and the dynamics of roosting locations. The breeding territory of the couple is also indicated by a rectangle, within which most of the morning and early afternoon data reside. This territory is used for daily activities such as feeding, and preening.

In Figs. 11(c)-11(d), the acceleration in the z- and x-axes for the SH-chick is shown, which reveals important insights on the small-scale movements. The absolute value of acceleration is heavily influenced by the gravitational force, especially in z-axis, and provides an information about the bird posture. It can be observed in Fig. 11(c) that during night, when the bird stays still, the sample variance is the lowest and the mean is close to $9.8 \mathrm{m/s}^2$. The morning and afternoon data exhibit higher variance and the higher acceleration values suggest flying ($\sim 0 \mathrm{m/s}^2$) and takeoff (positive values).

The acceleration in the x-axis shown in Fig. 11(d) has a similar trend in terms of the CDF shape. The steeper slope of the CDF during the night corresponds to limited movements compared to the morning and evening. The majority of the values during night are slightly higher than 0, which indicates the bird was standing still (see Fig. 4(b) for bird posture, x-axis points towards the tail). As shown in Fig. 11(a), during morning and evening, cranes generally do not fly and stay in their territory and roosting site, respectively. Consequently, x-axis acceleration can be used to reveal posture since the walking speed effects are negligible compared to gravity. The negative values suggest that the bird's head was leaning to the ground, which is a typical posture during feeding. Similar trends have been observed for the other cranes.

6. CONCLUSIONS AND FUTURE WORK

We have presented our work on developing and evaluating a tracking platform for Whooping Cranes, which present unique challenges in their mobility and extremely low population size. The developed cellular sensor network platform seeks to provide more detailed data on these birds' behavior. CraneTracker's design aims to provide multi-modal sensing and multi-modal communication capabilities that allow reliable and time-critical monitoring on a continental scale. Field experiments illustrate the low-delay in communication, which motivates the use of a GSM modem as a second communication device. Finally, the extreme rareness of the birds necessitates an extended testing plan on more abundant species.

In the future, we will investigate the potential of the 802.15.4 radio in our device. Given the close proximity of the family members during the migration, the short range radio can create multihop networks. These networks may allow for more efficient energy management, and the use of one of the family members to act as a gateway to the cellular network. Furthermore, the radio can be used in the nesting and wintering grounds, where the cellular service is not prevalent.

In the near future, the platform will be deployed on extended missions with captive-reared Whooping Cranes. These trials will provide the opportunity to evaluate the performance of the sensors and communication mechanisms under conditions more comparable to those that the AWBP experiences. Given successful field tests, the devices can then be deployed to the Whooping Crane population. The collected data from the Whooping Cranes will be used to identify and protect critical habitat areas for this iconic bird species.

7. ACKNOWLEDGMENTS

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