UAVs as a leverage to provide energy and network for Cyber-Physical Observation Units on the Arctic Tundra

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Abstract—Observing an environment is essential to its understanding. This is certainly true for the arctic tundra as it is extremely sensitive to climate change. Satellites are used to observe large areas of the arctic tundra. However, the measurements are not at sufficient spatial resolution to be used to determine the species of animals, and to measure humidity, temperature, and CO_2 levels for small areas. Ground-based measurements, which represent less that one percent of the experiments carried on the arctic tundra, must be done.

Deploying and maintaining ground-based instruments is hard to do because visiting the arctic tundra is expensive, time consuming, and dangerous. Instead, automation is needed, where instruments can operate independently for long periods of time, and allow interaction with remote users for reporting of data and control of the instruments. However, the arctic tundra also has, as a common case, limited data network and energy coverage.

We present the Distributed Arctic Observatory, where instruments called Observation Units (OUs) are distributed across the arctic tundra to measure a range of environmental state variables, and report them to where they are needed for further analysis.

The DAO project uses Unmanned Aerial Vehicles (UAVs) to provide backhaul network access and energy to OUs. The modifications applied to the UAV and to OUs are presented. We describe the experiences gathered from practical use of the UAV to provide network access and energy to OUs located on the ground at 70°N. We show that it is feasible to apply UAVs to provide network access and energy to OUs on the arctic tundra, albeit practical restrictions.

Index Terms—Cyber Physical System, UAV, monitoring, arctic tundra, Observation Units, network coverage, energy providing

I. Introduction

The arctic tundra is very sensitive to climate change [1]. By observing the flora, fauna, and environmental parameters of the arctic tundra, changes can be identified and tracked. However, presently only a few sites on the arctic tundra are monitored. The Climate-ecological Observatory for Arctic Tundra (COAT)[1] initiative is tasked with observing the arctic tundra, detect climate related changes, explain them, and advise the public and the authorities.

COAT researchers use several approaches and instruments to observe the arctic tundra [2], [3]. One approach is to use tens to a few hundreds of small dedicated instruments deployed according to where ecologists believe they can catch interesting events, like images of animals. The small instruments are deployed by humans during the summer season, configured in the field and left alone to collect data onto solid state disks. After typically two to six months, instruments are fetched from the field by humans and collected data sets are manually uploaded to a local machine, from where they can be further uploaded to a storage server.

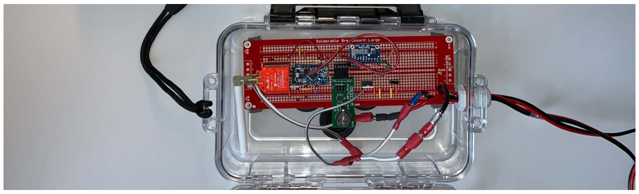
Such stand-alone instruments with a few simple functionalities are based on micro-controllers. They are cheap, small, and use little energy. They are well suited for embedded non-advanced tasks like reading a sensor and storing its value locally. But micro-controller based instruments have none or limited network support compared to computer-based instruments. For more advanced functionalities, instruments with tiny computers need to be used. These have much more resources and come with better programming support.

For instruments located on the arctic tundra with sparse network coverage, advanced networking functionalities are needed to increase the possibility of being able to report observational data. Instruments should be able to scan for available networks, determine which networks to use and when to use them to finally do the actual transmissions. Although, they should be able to turn the advanced functionalities "on" when needed and "off" when not needed, to save energy and to reduce the number of visits by humans to replace batteries.

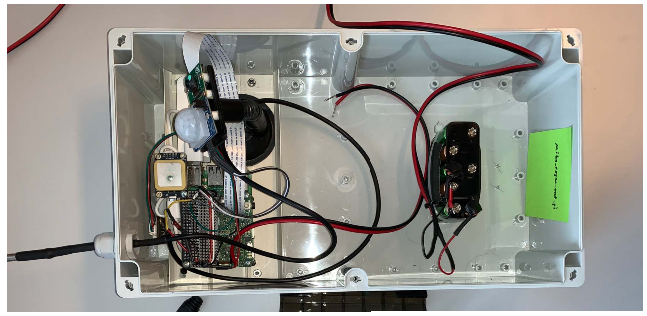
Computer-based instruments can compensate for higher energy consumption by using larger batteries to match the life time of the micro-controller based instruments. While larger batteries supports increased lifetime or functionalities, they rapidly increase in size, weight and cost. Moreover, large batteries are not practical for *general* use on the arctic tundra because of environmental concerns and regulations. Consequently, smaller batteries must be used. However, in such context, batteries must be recharged or replaced more often. This can be hard to achieve in the arctic tundra, which is a large area with unique and challenging weather.

Lower energy usage can be achieved for computer-based instruments. Although, there is a need for providing fast dissemination of observational data to researchers. Answering

[1]https://www.coat.no/



(a) Micro-controller-based OU with external battery



(b) Computer-based OU with internal battery

Fig. 1: Prototype Observation Units, to scale

TABLE I: Prototypes Observation Unit HW

Characteristic	Micro-controller Insect Trap	Computer-based
Computer	-	Raspberry Pi 3B
CPU	-	4 × ARM Cortex-A53 @ 1.2GHz
SoC	-	Broadcom BCM2837
Memory	2kB SRAM	1GB LPDDR2 @ 900 MHz
Micro-controller	Arduino Pro Mini @ 8 MHz	SleepyPi2
Networks	LoRa	WiFi, BT, LoRa, NB-IoT, LTE
WiFi	-	Broadcom BCM43438
Bluetooth	-	Broadcom BCM43438
LoRa unit	Semtech SX1276 (868MHz band)	Semtech SX1276 (868MHz band)
NB-IoT unit	-	ublox SARA-n210
GPS	-	ublox neo-6m
Optical sensor (Camera)	-	The Raspberry Pi Camera Module v2
Passive Infrared sensor (PIR)	-	Adafruit PIR
Humidity sensor	-	DHT22
Temperature sensor, internal	-	DHT22
Temperature sensor, external	-	DS18B20
ADC	ADS1115	-
RTC	DS3231M	-
Led strip driver	Mosfet: IRL B8721	-

these concerns with more sensors over large regions will consume even more energy. Consequently, either humans must expect to visit the instruments often, or alternative approaches must be found to provide for energy as well as connectivity.

In this paper, we focus on leveraging UAVs to provide energy and network services to instruments, and thus to reduce the number of visits needed by humans. To provide network services, a UAV does a rendezvous within WiFi or BlueTooth range of an instrument to either operate as a bridge to a back-haul network, or to be a store and forward network node for the instruments data if no suitable backhaul network is found. For delivering energy, a UAV does a physical rendezvous with a single instrument to recharge the instrument's internal battery, or replace the instrument's external battery.

This paper is structured as follows. Section II presents the Distributed Arctic Observatory System. Network providing by a UAV is presented Section III while energy providing is presented section IV. Section V presents related works. Section VI presents discussions about the contributions of the paper. Finally, section VII presents conclusions and future works.

II. The Distributed Arctic Observatory

For the rest of this paper we call an instrument monitoring the environment an *observation unit* (OU). This section presents two implementations of OUs, the Distributed Arctic Observatory system composed of many OUs, and how UAVs can be used as a leverage to keep OUs operational concerning two scarce resources: backhaul network access and energy.

A. The Observation Unit

The basic hardware components of an Observation Unit (OU) comprises one or multiple micro-controllers and computers, storage, multiple radio-based networks, sensors and batteries. The OU is packed into a waterproof container. The sensors and batteries can be both internal as well as external to the container.

A micro-controller based OU is shown in Figure 1a, while a computer-based one is shown in Figure 1b. Table I lists the components used in these two prototypes.

The micro-controller-based OU, here an insect trap, has no battery. It needs an external energy source. By turning a strip of LEDs ”on” and ”off”, the OU attracts, blinds and traps insects for counting purpose. The OU has a LoRa network,

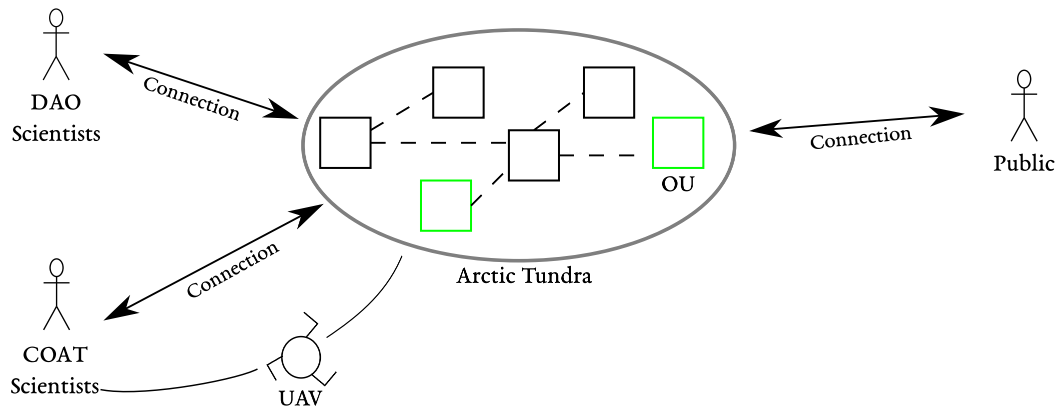


Fig. 2: Interactions of user with the Distributed Arctic Observatory

used to report its state to a LoRa OU gateway which in turn uses a WiFi network to relay the data to a WiFi access point. The WiFi access point is connected to a backhaul network for delivering the data to a back-end computer.

The computer-based OU is much more complex, and has an internal battery as well as an external battery platform. It has more sensors and network capabilities. Advance functionalities are supported by a higher number of operations per second and memory capacity. The computer, Raspberry Pi, is enhanced with a SleepyPi 2, Arduino based micro-controller, to completely turn the power ”on” and ”off”.

The software suite of an OU can, in the simplest case, be a sequential program with few functionalities. For more advanced functionalities a more advanced development and run-time environment is needed. For the Raspberry Pi-based observation units we use ”Raspbian Linux”, giving us a mature operating system with a rich set of services and tools. We add a range of programs for the functionalities of the OU. These include reading of the sensors, storing the observational data, establishing connectivity and reporting data to other OUs. An OU is also able to cover various ranges and various network activities by using different protocols (from LoRa to LTE). Most of these processes are presently implemented in Python to simplify the maintenance of the code.

For this paper we are ignoring the complete environment and functionalities needed to let an OU autonomously request a UAV to provide it with energy and network services.

B. Cyber-Physical System of Observation Units

The individual OUs are bound together to a distributed cyber-physical system, the Distributed Arctic Observatory (DAO). Figure 2 presents an overview of the users and the system. The oval represents the monitored environment, in our case the arctic tundra. An OU is represented by a square. Green and black squares represent two types of in-situ OUs with different set of tasks and sensors. A line represents interactions between users and the system. The direction of the arrows indicate that data flows from the system to users, and that commands flow from users to the system. The actual connections can be realized in several ways, including usage of backhaul networks, UAVs, or by other carriers of data like skiers. The dotted lines between observation units indicate one possible network link topology between them.

Ecologists (here COAT scientists) can interact with one or a subset of OUs. They can, for example, request all observational data using their own back-end computers. They can also ask about the internal status of an OU to check if a given sensor is collecting data or if it is broken. In the future, OUs will also allow access to other type of users. For instance, a public user could have access to data from publicly accessible OUs.

Each OU executes functionalities for its *local* operations and observations as well as functionalities for its *system-wide* integration into the DAO system.

C. UAV Use Cases

In this paper we focus on providing, with the help of a UAV, energy and network to a single OU. For OUs on the arctic tundra, there are several interesting use cases where UAVs are relevant because of their low cost, size, and weight.

One use case is to navigate by boat close to the shore, send a UAV up a mountainside or away from the shore to visit OUs inland. Another use case is to drive a car or a snowmobile into an area, then use a UAV to cross a river to avoid sending humans into polar bear or avalanche prone areas.

Assuming an OU has no or only low-bandwidth *backhaul* networks available, it may be able to transmit the observational data by multi-hopping through the high-bandwidth local networks of other OUs. However, one of the hidden cost for the sender is that each OU has to spend energy to forward the data. Thus, the overall energy consumption of the system increases.

A visit by a UAV provides an alternative path for the data to take. If an OU detects no backhaul and no local network, the UAV provides the only path out for the data. If a low-bandwidth backhaul network and a high-bandwidth local network is available to an OU, the UAV can provide a higher bandwidth to the backhaul. In this case the UAV first downloads the data from the local network, then flies to a high-bandwidth backhaul network area.

Assuming an OU needs to continue ongoing observations during energy shortage, it must do local energy harvesting, or be provided with energy. A UAV can be the energy provider. For energy-hungry or hard to reach OUs, using a UAV may be the only practical way of delivering more energy.

In principle, a UAV can deliver energy and network services directly to any OU. In practice, not all OUs can be reached because of several issues including limitations from the UAV (load capacity, flight time) and limitations from the environment (hard to reach locations, bad weather).

The next sections presents the use of UAVs to provide network and energy to OUs deployed on the arctic tundra.

III. UAV PROVIDING A NETWORK

This section presents how the UAV is modified as well as the experimental setup for evaluating the UAV as a network provider to an OU.

To use a UAV to provide either access to a backhaul network or a store and forward node, the UAV needs to be physically modified. The OUs already have both the hardware and software needed. The basic idea behind the needed modifications of the UAV is that OUs on the ground connect over a high bandwidth local network to the UAV. The UAV then connects with a backhaul network to forward the data.

We use WiFi as the high-bandwidth local network and LTE as the backhaul network. Bridging between them is done by an LTE broadband router. The UAV must fly within Wifi range of the OU. To extend the WiFi range the router is modified by adding a 2.4 or 5GHz directional antenna for the WiFi radio. The antenna is mounted onto two arms on the UAV making it possible to adjust the orientation of the antenna. The azimuth is adjusted by rotating the UAV around its vertical axis. By adjusting the altitude (elevation) and azimuth, the antenna can be pointed at an OU on the ground. If an LTE network is not found, the UAV can in principle use the ad-hoc connection it has to the OU on the ground to download and store the data.

A. UAV prototype

Table II presents details on the actual UAV prototype. The weight for the basic unmodified UAV is about 4Kg. The modifications (four servo motors, antenna, router) add 1Kg.

The DJI UAV is chosen because it can fly at full speed at a maximum weight of 6‹14Kg. Consequently, the UAV can carry simultaneously both 1Kg of network-related modifications, and about 1Kg of battery-related modifications. Alternatively, the UAV supports a battery payload of 2Kg. The heavier the payload, the less flight time can be expected.

The LTE router is chosen because it is lightweight (150g). It is also small, with a volume less than $500cm^3$, and can easily be fitted to the UAV. The router is rated to support a download rate up to 300 Mbps using simultaneous dual-band on both 2.4 GHz and 5 GHz. As it is an upper bound extracted from the specs, we don't expect to reach such speeds.

[2] zyxel.com/products_services/4G-LTE-A-HomeSpot-Router-LTE4506-M606/

TABLE II: Modified UAV description, Network

Characteristic	Value
Name	DJI MATRICE 200
LTE broadband Router	Zyxel LTE4506 [2]
Remote controller	FrSky Taranis Q X7 16ch
Weight	
Unmodified	3,8 to 4,35 kg
Modified	5,2 kg
Wifi antenna	
Model	Yagi type
Gain	Max 15 dBi
Battery Capacity	
UAV	2*4280mAh at 22.8V
LTE router	2600 mAh at 5V
Expected UAV range in practice	
Half payload, 1Kg	16Km
Max payload, 2Kg	10Km

The external antennas represented in yellow in Figure 3 can be adjusted in azimuth using servos, represented with blue boxes. The possible rotation points of the servos are displayed with arrows. The antenna's horizontal direction is also adjusted by rotating the UAV. The implemented module is mounted on the UAV as shown in the picture on the right side of Figure 3.

B. Network providing experiences

The aim is to demonstrate the feasibility of providing an isolated OU with a network carried by a UAV. The experiments are carried at about 70 degrees north at the Kvaløya island outside of the city of Tromsø, Norway. The temperature for these outdoors experiments is around -5°C with snow both on the ground and in the air. The WiFi frequency is set to 2.4 GHz for longer range. We could not fly the UAV higher than 120 meters because Norwegian legislation forbids flying UAVs higher without a flight plan.

Initially, the UAV is placed on the ground beside the OU. The router finds and connects to a 2G Edge network from Telenor (a Norwegian telecommunications provider). The OU boots-up and associates its WiFi network with the router on the UAV. The OU on the ground runs a browser with a website measuring bandwidth. Two websites are used [3] [4]. Both indicate same results.

We measure upload and download bandwidths of about 0.1Mbps on the ground. We then rise the UAV to 118 meters. The UAV is now above a small mountain ridge, to have line of sight to an LTE tower about 20KM away. Exploring multiple bandwidth measurements give an upload and download bandwidth around 10Mbps and 65Mbps, respectively.

We find out that it is easy for an experienced UAV pilot and instructor (one of the authors, Mjøen) to steer the UAV high enough between low mountains to locate a strong LTE signal, rotate the UAV in the azimuth to point the antenna in the direction of the OU on the ground, and adjust the elevation of the antenna downwards to point at the OU.

We do not measure how far the UAV can fly with the network-related modifications. Based on many experiences

[3] test.telenor.net
[4] speedtest.net

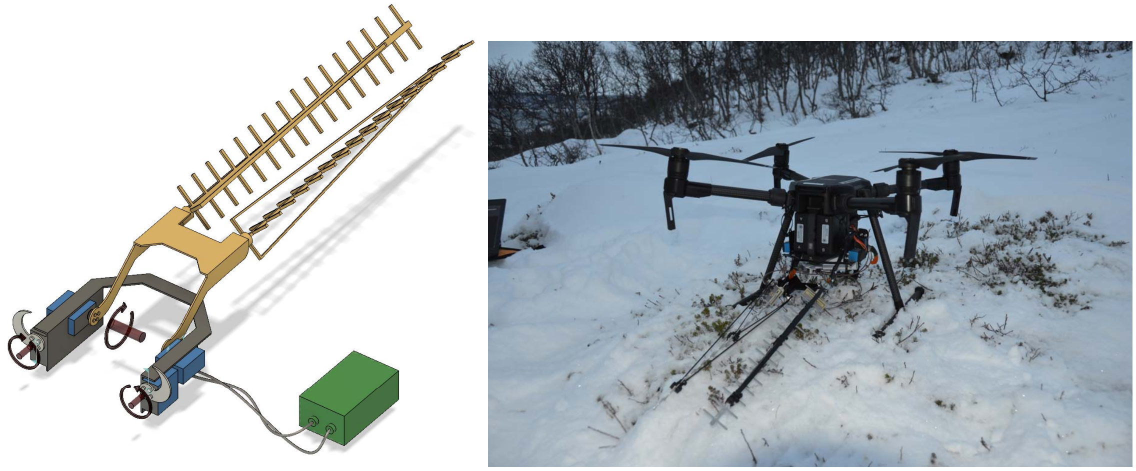


Fig. 3: 3D model of network and battery grip module

with drones, we estimate that the UAV is able to fly no more than 10Km with full 2Kg pay load. With half payload (1Kg) it can fly no more than 16Km. This can be significantly less at low temperatures and head-wind. Also, the antennas are relatively large and bound to be impacted by both wind and air resistance when flying, especially at full speed. All in all we don't expect to see longer than 10km round trip to visit an OU with this specific UAV.

IV. UAV PROVIDING ENERGY

This section presents the modifications done to the UAV, OU, batteries and battery platform to support energy providing by a UAV, followed by experiences.

A. UAV

Table III presents the characteristics of the chosen UAV and other assembled parts for the energy providing experiment. The same UAV is used as the one described under network provisioning (see Table II and Figure 3).

The UAV is modified to be able to grab a battery using two rotating claws, as seen on Figure 3 and on Figure 4b. To reduce swaying of the battery during flight and to prevent the battery from coming loose, two extra arms are used to push the battery against the UAV during flight. These arms also holds the antenna described earlier.

4 servos motors are installed to be able to rotate both the claws and antennas to catch the battery and point the antennas in the direction where network is needed. These servos are represented by blue boxes in Figure 3, along with their rotation point, represented with arrows.

TABLE III: Modified UAV description, Energy providing

Characteristic	Value
UAV Name	DJI MATRICE 200
Weight, UAV, unmodified	3,8 to 4,35 kg
Weight, UAV, modified	5,2 kg
Type, External Battery	Lithium LiFePO4
Capacity, External Battery	3.5 Ah
Weight, External Battery	800g
Servos	Power HD LW-20MG Waterproof

B. Observation Unit internal batteries

An OU is designed to have an internal battery fitting inside the box housing the OU, as seen on Figure 1b. This battery is carefully chosen to fit the usage of the OU with regards to capacity, voltage, discharge and charge characteristics at the temperatures it operates. Typically, an OU has a battery based on either Low Self Discharge (LSD) NiMH or NiCad technologies. NiMH and NiCad batteries can both charge at -30°C. However, a multi-cell NiCad battery package is more robust than NiMH with regards to being electrically mistreated when charging it to 100%. Unfortunately, the energy density is not as high as for NiMH batteries. Consequently, our first pick for the internal battery in an OU is a NiMH multi-cell pack. To avoid mistreating individual cells, we charge the whole pack to no more than 80% of max capacity.

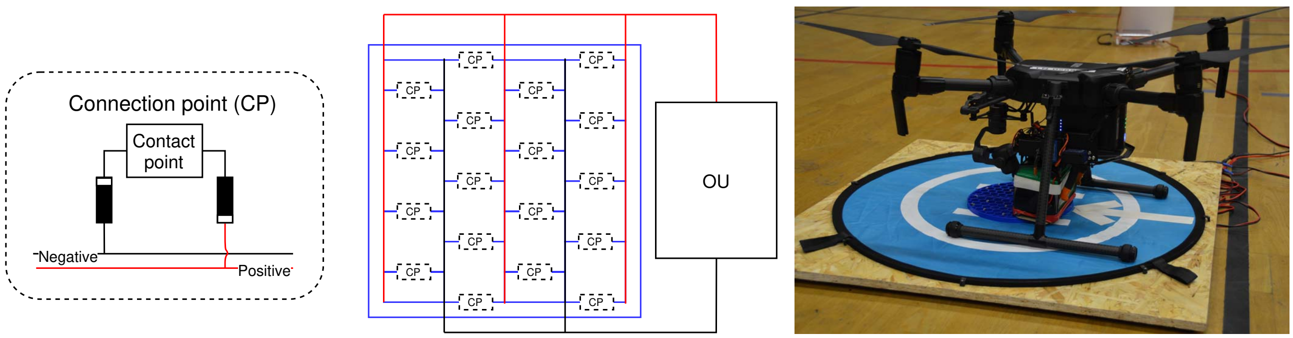
C. External battery

External batteries are modified by having two handles mounted, allowing the UAV to grab them. The battery has, on the bottom, two independent exposed electrical contact pads connected to the positive and negative connectors. This allows for positioning of the battery in any position on the platform to reduce the need for a very accurate landing by the UAV.

Compared to the batteries that are used on the OUs, the battery carried by the UAV has higher capacity and voltage, necessary when used for recharging instead of replacing batteries. It is also lighter, and with larger energy density.

D. Battery Platform

In addition to the internal battery, an OU can have an external battery platform, shown in Fig. 4a. External battery are placed on the platform. The platform accepts one or more batteries depending on the size of both platform and batteries.



(a) (b)

Fig. 4: External battery platform, schematic and picture

Figure 4a presents a schematic of the current build of the external battery platform. Each contact point (CP) consists of a contact with two diodes connected to it, one with the cathode connected to the positive wire and one with the anode connected to the negative wire. It ensures that if the CP is connected to the positive battery connection, the power will only flow from the battery to the positive side. Likewise, if the CP is connected to the negative battery connector, the power will only flow through the negative wire through the diode. The space between each CP guarantees that each battery connector will connect with at least one CP. The contact points on the battery are spaced far enough from each other to guarantee that a single CP on the battery platform can never make connection with both the positive and negative side of the battery.

As long as there is free space for a battery and that the two pads on the bottom of the battery make contact with a CP on the platform, it can deliver energy to a connected OU. Batteries can have different capacities and voltage without damaging each other. It allows hot-swap replacement of batteries. With extra circuitry, the battery platform can be enhanced to also allow for recharging of batteries, instead of swapping them. We do not discuss these features, as this paper focuses on the use of the UAV.

E. Providing Energy: test design and experiences

Figure 5 illustrates the complete set-up of the UAV, OU and battery platform. The UAV, on the left, rests on a battery on top of the battery platform. A cable connects the platform electrically to a multi-meter (for validation purpose), and to an OU on the far right.

The OU is an experimental insect trap that controls LED strips to attract insects, and communicates over LoRa to report state and receive updated plans for energy conservation (like LED blinking and duty cycling). In this experiment, the OU has no internal battery. When the UAV drops a battery onto the platform, the OU boots-up and turns the LEDs "on". When the battery is depleted or removed, the LEDs turn "off".

This set-up is used both indoor and outdoor. The indoor testing are done to rehearse for the outdoor testing, to avoid trouble-shooting initial issues in bad weather. The outdoor testing are done at temperatures well below zero Celsius.

The validation tests are done multiple times following the same pattern. We begin by taking off with the UAV, and fly it to a battery laying on the ground. The UAV lands onto the battery. It then closes its claws onto the two battery handles, and closes the two stabilizing arms around the battery. The UAV takes off with the battery mounted beneath it. The UAV flies to the battery platform and lands onto it. It then releases the stabilizing arms and the two grabbing hooks, to finally take off again. It may have to wriggle back and forth a little bit when landing onto a platform to make sure the battery makes good electrical contact with the platform. With our set-up, visual validation is easy, by watching the LEDs or the multi-meter.

In our experience, we successfully cover our validation protocol (land the UAV, grab the battery, fly to the platform, and place the battery so that electrical contact is made) at every round of testing both in the indoor and outdoor settings. However, the UAV was flown by an experienced pilot.

V. Related Work

During the last years, UAVs have raised interest in the network community as a possible leverage to deploy wireless networks for machines without network coverage. That growing interest is due to the fast and modular deployment that UAVs allow [4].

The various opportunities and challenges that wireless communication with UAV implies have been explored [4]. Three typical use cases are covered: (i) UAV-aided ubiquitous coverage; (ii) UAV-aided relaying; (iii) UAV-aided information dissemination and data collection. The use of UAVs raises a set of challenges with regards to coordination, security, limited amount of processing and energy available on a UAV. When using UAVs to aid in monitoring of the arctic tundra, all of the three network-oriented use cases are relevant.

Sensors are deployed in-situ in an environment to collect data representing possible states of the environment. However, sensors using batteries have limited energy available.

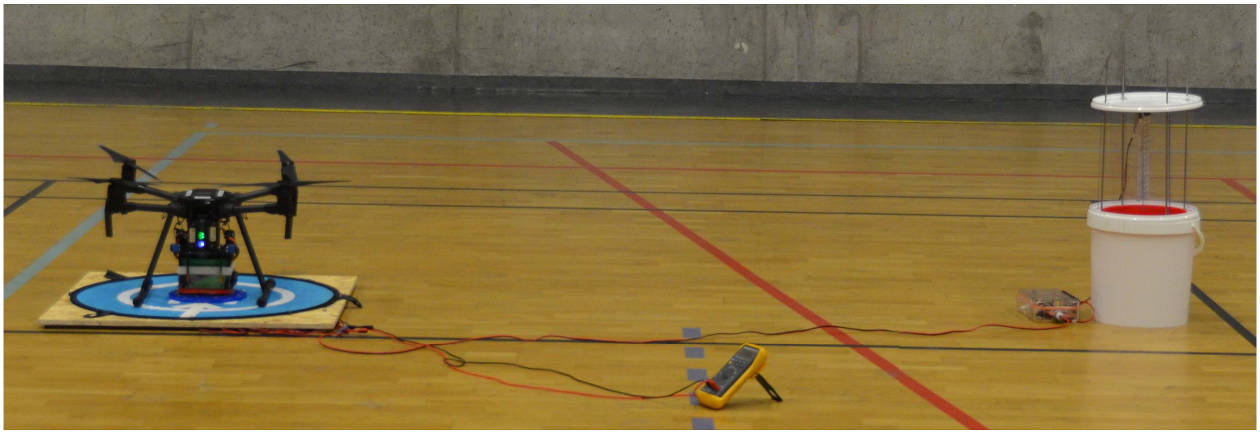


Fig. 5: Energy providing through UAV, complete set-up

Even with in-situ energy harvesting, energy must be carefully managed. Sensors can be coordinated to form a distributed cyber-physical system with the purpose of achieving improved non-functional characteristics like longer energy-limited operational lifetime as well as achieving increased functionality. Few papers attack the problem of delivering energy to sensors far away from energy resources using UAVs. One approach is to deliver energy through wireless magnetic resonance to a low power sensor [5]. The energy is drawn from the battery of the UAV. This is viable for very low energy needs. However, some of the sensors (built as an OUs) proposed for the arctic tundra need significantly more energy.

To visit an in-situ sensor by UAV, it becomes necessary to determine accurately where the sensor is located. GPS does not provide sufficient accuracy. One approach is to navigate around GPS coordinates, then do more accurate navigation based on sensing the magnetic field of the power transfer system [6]. This approach allows the UAV to localize the sensor with an average error of 15cm. Using induction charging, the sensor can be charged with an average power transfer of around 4.2W, enough to power low power sensors.

Extending this approach, a localization algorithm is used which lets a UAV align itself with the sensors power receiver by sensing the induced field [7]. Then the sensor battery is charged by magnetic resonant wireless power transfer. The system is lightweight enough to be carried by a UAV.

In summary, previous related works have shown that both the network and energy providing have benefits and challenges in the context of UAVs and distributed sensors. However, none of the previous papers proposed a solution for complicated ecosystem like the arctic tundra, where human presence can be limited or even impossible during long periods. No approach describes providing of network to computer-based OUs. Also, none of the previous papers have presented a solution for larger energy budget delivery. Finally, none of the previous papers proposes a solution to provide both energy and network, from the same UAV.

VI. Discussions

OUs do not require UAVs to operate as they are most of the time intended to be offline or working in low power modes to save energy. However, energy and network providing by UAV extends the lifetime and range of reach of OUs. It permits a quicker access to the OU compared to visiting sites by humans.

In our current set-up, a UAV carries a relatively large and heavy battery. The approach itself can be used for smaller batteries as well, allowing the delivery of smaller batteries using smaller UAVs to the OUs that don't need a lot of energy. The smaller UAVs cost less, use smaller batteries, and can be recharged faster. This in turn may lead to a hierarchy of UAVs. A few larger ones can recharge the batteries of many smaller UAVs already out on the arctic tundra.

To efficiently recharge batteries in-situ on the arctic tundra, the UAV should carry a battery of a higher voltage than the OU's internal battery. However, charging has multiple drawbacks at very low temperatures, including reduced efficiency or impossibility of recharging specific cell types. Thus, a battery OU can only be built from expensive technologies. Such limitations can become prohibitive when the number of units increase. However, UAVs can help in fetching batteries and bring them into a warmer environment where they can be recharged efficiently.

Induction is an alternative to physical contact for transferring energy from the UAV to the OUs. This is of particular interest if the battery platform is covered with snow or ice. Because it is not the main subject of this paper, results related to that energy transfer protocol are not covered.

UAVs could also be relevant during the deployment of OUs, dropping OUs at the right GPS position that needs to be monitored, instead of sending people into environments where freedom of movement is limited.

The OUs typically have GPS units built in. A relatively accurate positioning of them on the arctic tundra is therefore possible. This is valuable for several purposes, including finding the route a UAV should follow to optimize between a UAV's payload and the number of OUs that can be visited [8].

A fleet of UAVs can be used to form a wireless air-to-air multi-hop network [9]. The UAVs are positioned in a configuration that allows them to reach, or possibly move towards each other to make contact. Such solutions could be beneficial to a set of OUs distributed over the arctic tundra.

The arctic tundra is a complicated ecosystem, and optimization algorithms and models may need to be modified. Studied dimensions should include the route optimization, energy concerns, network concerns, the priority of the observation missions at each OU and the weather forecast.

VII. Conclusions

The arctic tundra is exposed and very sensitive to climate change. Observations of animals and vegetation can be used as indicators of this change. Ecologists therefore monitor the tundra using various kinds of instruments like energy-efficient wild-life cameras, but possibly without network connections. So far, only a very small fraction of the arctic tundra is monitored with sensors providing measurements at a resolution needed by ecologists to determine, say, the species of animals.

To increase the number and resolution of observations of eco-systems on the Arctic Tundra, the Distributed Arctic Observatory (DAO) project is developing and using instruments named *observation units* to let ecologists monitor and control observations using a wide variety of sensors. Observational data can, in common cases, be made available with delays measured in seconds, minutes, hours and days instead of in weeks and months.

Because of the environment where they are deployed, the observation units cannot expect to be visited often by humans with new batteries. They must be able to continue operating on a limited energy budget. The arctic tundra also has sparse and limited backhaul network coverage.

We have shown that we can use UAVs as a leverage to deliver network and energy to observation units that need energy and backhaul network access. Delivering these resources by UAV adds a flexible extension to where observation units can be deployed in practice in an environment where it is impractical and costly, and sometimes even dangerous, for humans to be.

For providing backhaul network access, a UAV is modified with an LTE-to-WiFi router, two antennas, and two servo motors to adjust the altitude (elevation) of the antennas. The UAV is also modified with two servo motors with rotating hooks to be able to pick up, fly with, and drop off a relatively heavy battery.

To provide backhaul network access, the UAV lift from the ground and flew to get above a small mountain for line of sight to an LTE tower 20KM away. The upload and download bandwidth increased by at least two orders of magnitude to 10Mbps and 65Mbps, respectively. Controlled by an experienced pilot, the UAV steered to a strong LTE signal, rotate to point the antenna in the direction of the OU on the ground and adjust the antenna downwards to point at the OU.

With the modifications in place, the used UAV can carry a 1Kg battery. The intended target is a battery platform externally connected to an observation unit. For an experienced pilot, it is easy maneuvering the UAV, picking up a battery from a snow covered ground, flying to the battery platform, and finally placing the battery correctly on the platform.

Future work includes developing an ice resilient battery platform which can transfer energy by induction as well as using direct physical contact. This platform is less impacted by ice and snow. With such a solution, the UAV does not have to be very accurate when releasing the battery. The battery platform can also be used directly by humans to replace or recharge batteries with a minimal interaction. We also plan to embed an OU on the UAV, so it could act as a store and forward device. Future work also includes developing an algorithm finding the best trajectory for a UAV to visit OUs that are in need of either energy and/or network.

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Two videos were shot during use of the UAV for network and energy provisioning of observation units. They can be found on Youtube[5]. Thank you very much to Eirik M. Jensen for editing the videos.

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