Final report

1.1 Project details

Project title	Energy efficient drone inspection system for spotting leakages
Project identification (program abbrev. and file)	EUDP 15-I, 64015-0072
Name of the programme which has funded the project	EUDP – Energy Efficiency
Project managing company/institution (name and address)	DTU Fotonik Ørsteds Plads, Bygn. 343, 2800 Lyngby
Project partners	Zeuxion Sky-Watch
CVR (central business register)	30060946
Date for submission	July 2018

1.2 Short description of project objective and results

The goal of the project is to develop and demonstrate a drone based system for inspection of energy systems and distribution. A prototype drone with an on-board platform with light-weight video and IR cameras system was developed, analyzed, and optimized. In the basic prototype, the image data from the cameras can simultaneously be stored on-drone and streamed to the ground as one or two camera feeds. A light weight fixed wing drone was chosen for long flying time and distance. The drone system was designed for inspection of district heating and transmission line energy loss. For night time flying, a low-light camera was added in the advanced prototype. The drone based solution was tested and demonstrated at the HCA Airport.

Projektets mål er at udvikle og demonstrere et dronebaseret system til inspektion af energisystemer og – distribution. En prototype drone med en on-board platform med letvægts video- og infrarødt kamera system blev udviklet, analyseret og optimeret. I basic prototype kan billeddata fra kameraerne samtidig lagres of streames til jorden som et eller to kamera feeds. En letvægts drone med faste vinger blev valgt for lang flyve-tid og -afstand. Drone systemet blev udviklet m.h.p. inspektion af fjernvarmesystemer og højspændings transmissions-ledninger. Den dronebaserede løsning blev testet og demonstreret I HCA Lufthavnen.

1.3 Executive summary

The project achieved the primary goal of making a prototype lightweight automated drone capable of inspecting energy systems e.g. searching for energy leaks.
The technical focus was a to develop an on-board solution to provide real-time low-delay video and infrared imaging by transmission to an ground computer as well as storing the data on-board. The video link can be controlled and adapted for the video and transmission bitrates to adapt to the transmission conditions. The operator can choose between the signals of the cameras (sensors) or as an extension have both camera feeds streamed. The streamed data can be displayed in real-time on the ground computer. While the streamed data are adapted to the available bandwidth, the specified full quality of both cameras is stored on-board.

A key technological solutions to achieve this was an efficient video compression scheme, which can also be executed efficiently in terms of power H.264 was chosen for this and it can be executed on-board both in hard-ware and soft-ware. A hardware suited for drone integration (IMX6) was chosen for the implementation. The image and video streams were interfaced to an on-board transmission module. Both thermal IR and visual EO (RGB) cameras of low size and weight were integrated. The scope was extended by a low-light camera useful for flying at night time or when dark, which is use full for inspection of district heating. The solution was designed for inspection of district heating and power lines. Two prototypes, a basic and an advanced, were established and both were tested. Initial testing was performed on energy systems and the prototypes were demonstrated at the HCA Airport
Concurrently with the technological development, investigation of the commercial aspects were conducted, one conclusion being the biggest market potential lies internationally. The low-weight fixed weight drone with the developed camera systems seems to have a good position on the market, see also Sec. 1.6.

1.4 Project objectives

The project objectives as described above were to develop a lightweight energy efficient drone solution with IR camera and visual camera, which can stream the data to ground, for energy inspection.

The project was as planned organized in two steps, first a basic prototype, which subsequently was enhanced in the advanced prototype. The project followed the structure and sequence of milestones planned. First the technology was analyzed, the IMX6 board chosen and the video codecs, h.264 and h.265 were tested among others for technology clarification and the Flir IR (Boson) camera was chosen (M2). Thereafter the hardware was integrated, incl. the interfacing of board, cameras, flight controller, gps etc. and the software for integration and software for processing and for providing both hardware and software image and video coding written and integrated for the basic prototype (M3). DTU Fotonik and Zeuxion were responsible for these tasks in collaboration with Sky-Watch. Thereafter Sky-Watch integrated the camera and video payload into their Cumulus fixed wing drone and the basic prototype was tested and flown (M4). Based on the basic prototype, the advanced prototype was designed. It was decided to follow through to have an IR camera with resolution 640 x 512. While Flir had announced a 640 version of the Boson, the project could not wait for the delivery as it was being delayed and there was not a certain date. Another Flir IR 640 (Vue) was chosen instead. Also to enhance the camera solution and provide for visual feed during dark hours, it was decided to include a low-light camera (from Sony). It turned out that converters were needed to integrate the cameras, including these the hardware for the M5 was in place and later the software was done by Zeuxion and DTU Fotonik. So a late delivery of cameras and the following integration work with converters led to a small delay of the project, which was applied for and granted, see below. The advanced prototype was integrated by Sky-Watch. Due to the increased size and weight of the low-light, the solution for the advanced prototype was to install the new IR camera on the fixed wing Cumulus and the new low-light on a hexacopter, i.e VTOL drone.

The project evolved along the path laid out in the original plan as expressed by the milestones, see above. Striving to use the newest technology suited for high performance and low-weight for the drone, one risk was the timely availability of information, hardware and cameras. The major change in plan here was to abandon waiting for the Flir IR Boson 640 IR camera, which was early on identified as very suited for the project. On a similar note sparse info about the low-light camera and late delivery, also meant a delay as the final design had to be made after delivery.

On the organizational side, some activities of the initial project partner Little Smart Things, was due to economic reasons early in the process of the project, acquired by Sky-Watch. This also led to a reorganization and the drone activities were shifted from Bornholm to Støvring.. The project organization was also reorganized and the project duration extended due to have time to do the reorganization. The original technical plan as described above was overall maintained and followed throughout the project with the milestones shifted at the two times the project was reorganized. Thus the unexpected reorganization and delays in availability of cameras can be seen as project risks, which were mitigated by extending the project period within the same total budget, and modifying the design based on available camera and components, but the overall plan was maintained.

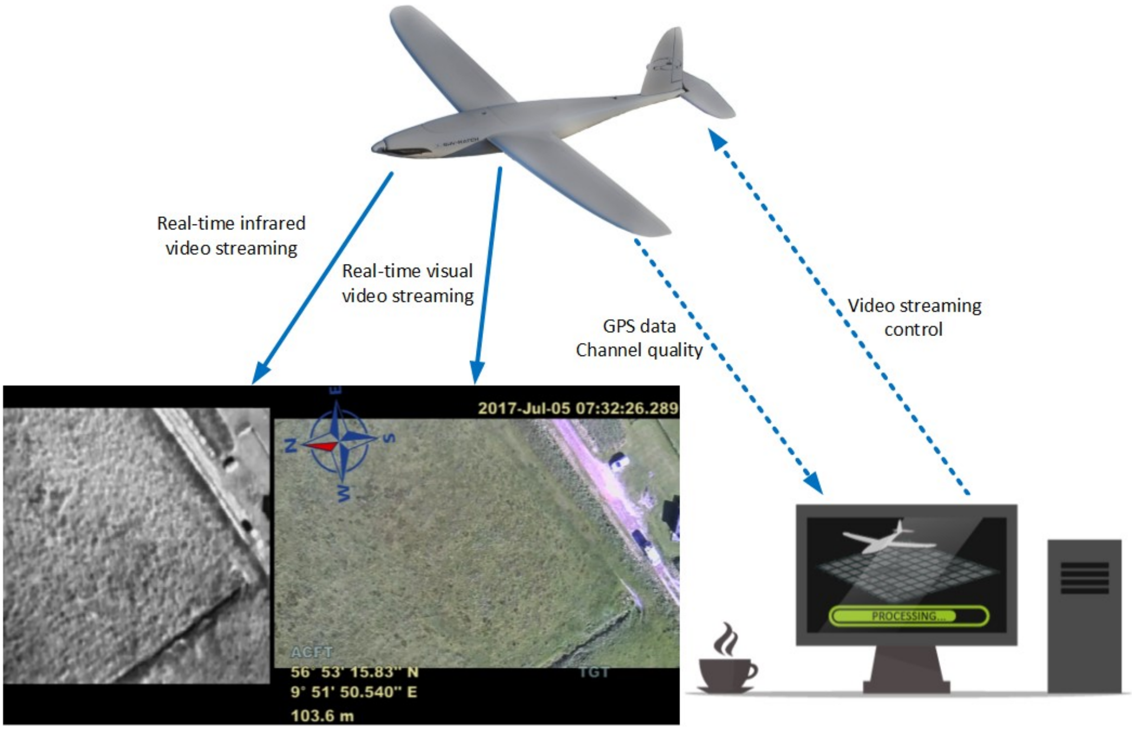
For the commercial track, it can be noted at a high-level that transmission and distribution (T&D) operators and utilities across the globe are beginning to look toward UAVs to reduce costs, improve safety, and increase reliability and response times across their systems. These new utility solutions include drone and technologies for transmission and distribution (DRTD). For further development of the prototypes, it has been concluded that minimizing the technology, it will have an export potential, see Secs. 1.5 and 1.6.

1.5 Project results and dissemination of results

The project was, as planned for the technical work, organized in a basic prototype and an advanced prototype. Both prototypes included on-drone video and IR images and they were flown and tested. The basic prototype was flown at the Støvring model plane airport including transmission lines. The advanced prototype was demonstrated at HCA Airport, Odense N, as well as flown on a solar energy system. Between the two prototypes thermal IR cameras, a low-light camera and conventional visual (EO) cameras were flown. Both prototypes provided on-board storage and real-time down-link. In this subsection we first present the technical results in more detail, then discuss commercialization aspects and then we list the project dissemination activities.

Basic prototype of on-board hard.ware, HW.

The Basic prototype on-board video solution was first established in hardware, HW, (WP4, M4) and integrated on a Sky-Watch fixed wing drone (WP5, M5) and successfully flown for test and demonstration. The on-board HW provides a platform for flexible interfacing of different cameras. Our development for the basic prototype focused on the (thermal) IR camera. A new IR camera type from FLIR (Boson) was chosen as it is smaller and better suited for flight and compact integration on drone than previous IR cameras from FLIR, which were originally planned for. The HW board was established by Zeuxion incl. SW with support from DTU. Sky-Watch provided IR camera and flight controller incl. GPS and they conducted the integration into their drone. The GPS data are captured and integrated in the image/video-data as meta-data. Two imaging streams (IR and video) are captured and stored on board in high quality based on the camera outputs. Interfacing with the on-board transmission unit provides streaming to ground of one selected stream coded to the available down-link capacity, as originally planned, and extended with the option of streaming two simultaneous streams. The Basic prototype set-up is illustrated in Figure 1 (note: in the field a laptop is used as ground computer.) The drone was successfully flown for test and demo. The functions as described above were tested and their operation confirmed. The demo included the on-ground integration and real-time of two video-streams and GPS location. The basic prototype was flown and tested near Støvring in a smaller airport for model planes.



Figur 1. Set-up and test of Basic Prototype. Image and metadata from test-flight.

Advanced prototype (AP)

The work on the Advanced prototype was initiated (WP6), based on the platform from the basic prototype, starting with SW updates and planning for extensions. The streaming of two sequences was already established as part of the basic prototype, otherwise extensions on the platform included making it more robust, flexible management of two cameras are implemented, streaming 16 bit IR images, embedding meta-data in image/video files incl. at a finer temporal granularity. This work is documented in conference papers presented at two international conferences [2,3]. Based on the results of the basic prototype and the general development of technology, a major enhancement was to select and integrate a low-light camera as an option for night/low-light inspection of district heating. The low-light camera has high sensitivity and is extended beyond the visual spectrum into the near-infrared. Thus it has the capability to capture images and video in conditions and resolve details, which goes beyond the capability of the human vision. Availability of a higher resolution Flir Boson IR camera was anticipated for quite some time. As this kept being delayed another Flir thermal-infrared (IR) camera with the desired resolution (640 x 512) was chosen and integrated on the fixed wing drone. For both of the new IR camera and Low-light camera converters/grabbers were required for the interface.

The HW payload platform to AP was completed in accordance with the (revised) time schedule. The software was developed by Zeuxion and DTU Fotonik and transferred to Sky-Watch, this included the updated interfaces to accommodate the converters to the new cameras. Data from both cameras can be stored on-drone and also streamed to ground. The flight controller data, e.g. GPS is stored and streamed in sync with camera data.

In the integration phase to integrate the payload HW on the drones, a number of challenges were encountered. The housing of the low-light turned out to increase size and weight of the camera considerable. This combined with the increased weight lead to the decision of mounting the IR on the fixed wing, while the low-light was shifted to a hexacopter, i.e. a VTOL, see Figure 2.

Test and demo-flight and project demo.

The advanced prototype was flown at HCA Airport on May 4, 2018 for testing and demo of the prototype. As described above, this involved flying two drones. The fixed wing was flown with the Flir 640 x 512 IR camera. The low-light camera was flown on a hexacopter. Both drones are shown on Figure 2. Streaming and display of images were also shown as well as the route planning which can control the drone flight, with an operator ready to step in.

a)

b)

Figure 2. Drones used in the demo: a) fixed wing drone, Cumulus from Sky-Watch, b) hexa-copter

Demonstrations at HCA airport.

First demos were presented on-ground at the project demo. This included:

Basic prototype HW, real-time demo of on-board capture and processing and connection with ground computer:

1. Infrared or visible cameras with streaming (one or two cameras).

2. Changing the bit rate of the streaming connection on-the-fly.

3. Changing the resolution of the video on-the-fly.

4. Metadata as gps inserted on-drone in video stream, transmitted and displayed on-ground via UAV player

5. Playback of a recently recorded drone video.

Advanced prototype HW, real-time demo of on-board capture and processing and connection with ground computer:

1. Infrared and low-light camera with streaming (one or two streams)

2. Low-light (LL) camera demo showing that it can provide visible images in dark conditions, also when even the human eye cannot see any details

Processing of drone video, off-line demo of recording images and video:

1. Demo of night capture using Low-light camera.

2. Tone mapped infrared video obtained from Flir Vue IR camera with and without indication of hot objects for initial leakage detection.

3. Tone mapped infrared map of solar panels with 'hot' objects marked by red color (obtained by stitching of images provided by Flir Vue IR camera).

4. Playback of a low light video also displaying metadata and position of the drone on a map.

5. Video with both visible and infrared images obtained from Flir Duo Pro camera.

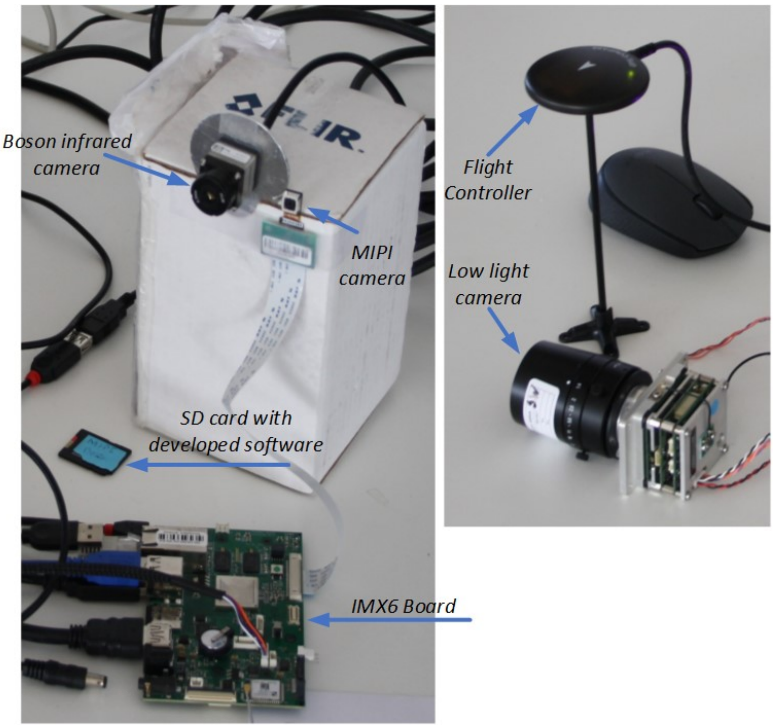
The off-line demo also included the stitching of prerecorded data into a mosaic solution. It may be noted that due to lower resolution and generally less contrast in the IR images, it is challenging, but doable to stitch the IR, especially when flying in areas with few objects with heat signatures.

Drone demo comments:

The Sky-Watch Cumulus plane has some unique features making it suited for low-cost aerial inspection. Being a fixed-wing plane it has in its price range, a relative large flying time, speed and coverage. The plane may be launched by one person, see Figure 3.

Figure 3. *Launch and landing of the Sky-Watch Cumulus plane at the demo at HCA Airport.*

The basic on-board payload hard-ware is shown on Figure 4. Software was developed to integrate cameras and equipment together and into the Sky-Watch drone. Different versions and set-up are easily interchangeable by copying a given version of the software into the SD card. This was also demonstrated at the project demo. The equipment of the basic and advanced prototypes are specified in the Annex.



Figur 4. Main components of the on-board payload of basic and the advanced prototypes

Figure 5 shows the performance between ordinary (Logitech) camera and the low light camera under dark light conditions. One can see that the low light camera should be used during night time inspections.

a) b)

Figure 5. Comparison of an ordinary camera (a) and the low light camera (b) under dark light conditions

Comparing fixed wing drone and hexacopter, during the demo, it is demonstrated that the fixed wing drone can cover relatively large areas, i.e., it is more preferable for long inspections in terms of both distance and flying time. For inspections of smaller areas the hexacopter may have advantages, since it can fly with very low speed and be more flexible in the rute.

For inspection of larger areas and/or longer distances of fixed infrastructure, rute-planning works well with the fixed wing, e.g. for district heating covering large areas and power lines for long distances. For district heating flying the 640 IR camera should provide sufficient information, supplementing with low-light at night time or EO when less dark will enhance the data, e.g. by increasing resolution. For the power lines, fast, cheap and energy efficient long distance visual inspection e.g. for vegetation is technically feasible. Here legislation for flight beyond visual line of sight will play a role. The rules will differ between countries on different continents. For high detail inspection, further investigation into e.g. multi-frame processing or enhancing camera capabilities is needed.

As it was measured, the IMX6 board with the developed prototypes consumes 5-10% of the drone battery, i.e., it is not reduces significantly the flight duration. So even in the prototype version, the selected and developed solution achieves the goal of providing an energy efficient on-board solution.

Analysis and investigation of image processing and coding techniques

Optimization of video (WP3) was a continuing effort in the project. This included novel methods for coding of IR images leading to the novel solution for on-board coding of 16 bit IR images, facilitating flexible and robust streaming of 16 bit IR to ground. As part of this and for preprocessing prior to the existing on-board 8 bit codecs, tone-mapping of IR images have been studied and new methods developed and implemented in SW both for on-board and on-ground use. The former was used for interfacing codec and efficient streaming, the latter with focus on visualization. This will also be useful for good quality on-ground reproduction of the 16 bit IR on commercial displays and benefit the user (interface). Work on on-board compression and processing of IR images on drone is detailed in [2] and [3]. Work on on-ground quality evaluation in [5]. In order to reduce the bandwidth needed for video streaming from drone to the ground, a novel drone high dynamic range infrared video coding algorithm based on aerial map prediction has been proposed. At the drone side, input frames are accumulated in a buffer and used to build an aerial map. Then the aerial map is used to predict new frames. Experimental results show that such approach provides up to 30% bit rate savings comparing to the ordinary coding via H.265/HEVC video coding standard [4].

Project results – technical status

To sum up the technical status, the project succeeded in realising its objectives in form of the basic and advanced prototypes for a drone with IR and visual camera with meta-data integrated. The data can be stored and streamed in real time at the same time. The drone system can technically be used for drone based energy inspection. The project was extended with the low-light camera option.

Commercialization of results and expectations of the project

Regarding commercialization (WP8), an internal document outlining possibilities and initial marked analysis and biz plan for Denmark was been written (CM3) and distributed to the commercial partners of the Advisory board (CM2). The advisory board partners are Rambøll, IBM, Aalborg kommune, DroneSystems og Scopito. A conclusion is that the main potential for e.g. Sky-Watch lies internationally. A second internal business document was written in 2018 with focus on the international perspective.

Both Sky-Watch and Zeuxion have increased employment based on the project. Sky-Watch increased with 1-2 people in the development department and Zeuxion with one person in development. The project is yet to result in direct export as the core technology is still too heavy to be commercialized on the current UAV platform.

If the technology can be minimized, the technology will have an export potential not only within energy inspection but also search & rescue and security applications. It may further be noted that legislation plays an important role as part of the market situation.

Dessimination:

The project and the perspectives were presented to the Advisory Board, constituted by representatives of both large and small companies with interest in the area of energy inspection using drones as described above. The advisory board was established in part as part of the commercialization activities. The advisory board constitutes a much targeted group for dissemination. Broader dissemination activities are listed below:

The project was presented at the annual drone event: TUS Nordic'17, Odense, Oct. 2017. A roll-up poster about the project ('Energy Infrastructure Inspection by Drones') was presented at the stand of Sky-Watch.

Activities and work from the project has been presented with a scientific focus *internationally* at (see also publication list in Annex):

- A Dagstuhl workshop on Imaging in Germany, Presentation on Nov. 2016.
- PCS (Picture Coding Symposium) 2016 in Germany, Dec. 2016 ('Low Complexity Video Encoding for UAV Inspection' [1]).
- Elec. Imaging (EI) 2017 in CA, USA, Jan. 2017 ('Compression of Infrared images'), EI 2018 ('No Reference Prediction of Quality Metrics for H.264 Compressed Infrared Image Sequences for UAV Applications')
- SPIE'17, USA ('High bit depth infrared image compression via low bit depth codecs')
- VCIP'17, USA, ('Low-complexity Compression of High Dynamic Range Infrared Images with JPEG compatibility')

The project has also been *presented* at relevant events *at DTU:*

- Grøn Dyst (Green Challenge) at DTU, 24.6 2016:
  H. Petersen and O.L. Christiansen (DTU Fotonik students), Drone Based Aerial Inspection of Energy Systems, Grøn Dyst 2016, DTU:
- DTU Student Drone Day at DTU, 28.6 2016. H. Petersen and O.L. Christiansen, Drone Based Aerial Inspection of Energy Systems, DTU Student Drone Day, 2016.
- DTU Drone seminar 2018: S. Forchhammer, Presentation on the DroneLeakage project and related activities.

The project has been used as case in a number of courses at DTU Fotonik, incl. the courses: 34251, 34240, 34241, 34220. Also some students have performed course projects in relation to the EUDP drone project. Four bachelor students and one master thesis student have performed their thesis project in connection with the EUDP drone project.

1.6 Utilization of project results

Sky-Watch will focus on commercializing the thermal mapping payload and the experiences gained in stitching together thermal images with low details. It will furthermore be investigated whether the lowlight camera technology can be minimised to fit small hand launched drones.

The technology will be presented in outlines for selected commercial partners in during Q4 2018, as it was defined in the business plan per Q1 2018. Depending on the outcome of these discussions the business plan will be updated.

Throughout the project elements of the project have been implemented in the core product offering. Moving forward Sky-Watch will focus on the individual payloads explored through the project and evaluate effort required to take it to the market. This effort is supported by the fact that there today still are no sub 3kg drones capable of thermal and lowlight mapping.

There are no plans to take out patents at the completion of the project.

Sky-Watch will continue to explore new payloads as the project has opened our eyes to the potential of new sensors that can open new markets. The project has increased our understanding of what it requires to do onboard processing of video.

The technology holds the potential to benefit utility grid infrastructure worldwide, especially in inspection of transmission and distribution power lines, but also in other associated services like vegetation assessment of trees and plants, power outage detection and response, security and surveillance of utility grids and district heating system storm damage assessment.

This EUDP project fits with the utility grid inspection application: Overview of the general state of the utility grid which often covers large areas. It is suited for medium inspection intervals. Using a fixed UAV as the Cumulus, large areas can be covered cost-effectively and the quality of the images is sufficient also at the speed of the fixed wing. The fixed wing drone will be able to cover an area of 160.000 m^2 in one flight (1.5-2 hours). VTOLs can complement in complex sections, where the fixed wing may be challenged.

Pain point	Impact	EUDP Value Add
Today the service companies are mainly using VTOLs inspection, this limits the areas that can be covered in one flight	The cost of data acquired with VTOLS will be higher than if the data was acquired with a fixed winged, as more time is needed to inspect/survey the same areas increasing the cost per sqm surveyed	Enables that Fixed Winged UAVs can be used instead of VTOLs for inspection of large infrastructures such as energy
When mapping an area with a thermal camera the level of details is very low making it difficult to distinguish objects	Wrong classification of potential issues can result in a less efficient response	Enables that the users either in real time or post can see the two video streams simultaneously and due to the embbeded meta data
Operators today are to a wide extent limited to daylight operations	The coming EU regulations for BVLOS operations is likely to include a requirement for a front facing camera.	EUDP enables that a downwards facing camera can be combined with a front facing camera,

The combination of images from different cameras, furthermore enables stitching into a map even of thermal mapping captured at high speeds.

The EUDP technology addresses an existing market with a new product offering. This enables the consortia to leverage on Sky-Watch existing distribution channels. Zeuxion could be part of a commercial partnership with Sky-Watch.

The 1st target market will be the existing market within inspection of underground district heating utility infrastructure by offering the operators with more flexibility when solving a task primarily to customers in EU and Asia. Thereafter the technology will be applied to other infrastructure inspection and mapping missions and lastly new markets will be pursued e.g. search and rescue operations where thermal mapping and night operations will be of high value.

For DTU Fotonik and the other partners, further innovation and research could lie in, e.g. (semi-) automatic analysis of the image data captured and inspection of other energy systems. In a test flight, PV solar plants were overflown and image data captured.

1.7 Project conclusion and perspective

In course of the project two prototypes solutions for cost-effective drone based inspection of energy (distributions) systems, as district heating and power lines, were developed, implemented and tested. The basic concept for the payload involves a thermal IR camera and a visual camera, which can simultaneously be stored on-board and real-time streamed to ground. One or two streams can be streamed simultaneous and the operator can select the streaming set-up on the fly. The image/video data coding for streaming can adaptively be adjusted to match transmission conditions. The light Cumulus fixed wing drone was chosen for light cost-effective and power-effective fast inspection with large coverage. The Cumulus fixed-wing, generally provides a faster solutions with longer operation than comparable VTOL solutions.

Working with three different camera types, IR, visual low-light, and many different cameras on the same platform, a very flexible platform, which can be integrated in the light weigh fixed wing drone for prototyping was developed.

If the technology is minimized the technology will have an export potential not only within energy inspection but also search & rescue and security applications.

Annex

Project publications:

1. J.Søgaard, Ruo Zhang, S. Forchhammer, Kabir Hossain, Low complexity video encoding for UAV inspection, *IEEE Proceedings of the 32nd Picture Coding*, Nuremberg, 2016.
2. E.Belyaev, C.Mantel, and S.Forchhammer, Low-complexity Compression of High Dynamic Range Infrared Images with JPEG compatibility, *Proc. IEEE Visual Communications and Image Processing (VCIP)*, 2017.
3. E.Belyaev, C.Mantel, and S.Forchhammer, High bit depth infrared image compression via low bit depth codecs, *Proc. SPIE Optical Engineering + Applications, Infrared Remote Sensing and Instrumentation XXV*, 2017.
4. E.Belyaev, S.Forchhammer, Drone HDR Infrared video coding via aerial map prediction, accepted for *Proc. IEEE International Conference on Image Processing (ICIP)*, 2018.
5. K.Hossain, C.Mantel, S.Forchhammer, No Reference Prediction of Quality Metrics for H.264 Compressed Infrared Image Sequences for UAV Applications, *Proc. Electronic Imaging Symposium, San Francisco*, 2018.
6. K. Hossain, C. Mantel and S. Forchhammer, NR Prediction of Quality Metrics for H.264 Compressed IR Sequences for UAV Applications, *submitted to Signal Processing. Image Communication*, 2018.

7. C. Mantel, J. D. Andersen, S. Forchhammer, On the evaluation of global infrared dynamic range reduction algorithms, to be submitted to *Journal of Infrared Physics and Technology*
8. E.Belyaev, S.Forchhammer, Low-complexity Open-loop Coding of IDR Infrared Images with JPEG compatibility, *to be submitted to IEEE Transactions on Multimedia*, 2018.
9. E.Belyaev, S.Forchhammer, Infrared video coding via aerial map prediction for multiple drone inspections, *to be submitted to IEEE Signal Processing Letters*, 2018.

On-line articles about the project and project home page.

”Partnerskab bag nyt drone- og kamerasystem,” på Energy Supply (http://www.energysupply.dk/article/view/222533/partnerskab_bag_nyt_drone_og_kamerasystem#.V5tP1k3r1aQ), 6.10. 2015

”Nyt dansk droneprojekt skal gøre energi grønnere,” UAS Nyhedsbrev, https://www.uasdenmark.dk/reditem/itemdetail/176-nyt-dansk-droneprojekt-skal-gore-dansk-energigronnere

Project home page: http://www.fotonik.dtu.dk/english/research/communication-technologies/coding/coding_research/droneproject

Technical overview of Advanced and Basic Prototype HW

Both of the prototypes on-board HW prototypes were based on the IMX6 board from Boundary Devices and integrated with flightcontroller, gps and transmission unit provided by Sky-Watch. A brief overview of hardware units and connections are given below.

Basic prototype:
1. Laptop (on-ground)
2. IMX6 Board
3. MIPI Camera (plugged to the IMX6)
4. Boson Infrared Camera (plugged to the IMX6 by USB2)
5. Flight Controller (plugged to the IMX6 by USB3)
6. Switch (for Ethernet connection between Laptop and the IMX6)

Items 2.-5. specify the on-board HW.

Advanced prototype:
1. Laptop
2. IMX6 Board
3. Low light camera (plugged to SDI->USB converter)
4. SDI->USB converter (plugged to the IMX6 by USB1)
5. Power supply (for the Low light camera)
6. Boson Infrared Camera (plugged to the IMX6 by USB2)
7. Flight Controller (plugged to the IMX6 by USB3)
8. Switch (for Ethernet connection between Laptop and the IMX6)

Items 2.-7. specify the on-board HW.