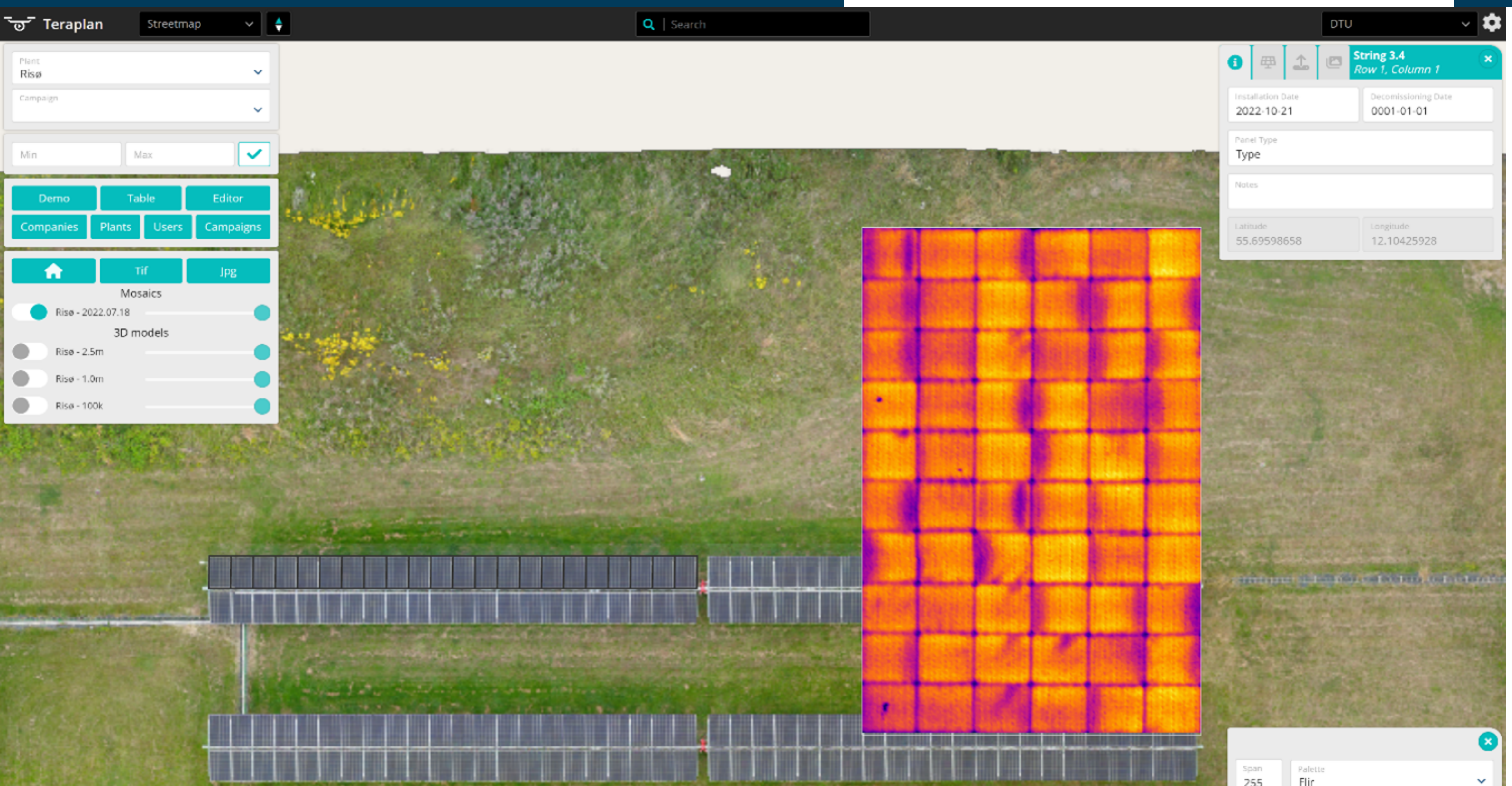
EUDP

EUDP 64019-0603

DronEL - Fast and accurate luminescence imaging of PV installations

FINAL REPORT



PROJECT PARTNERS

AALBORG UNIVERSITET

UXV TECHNOLOGIES

DRONESYSTEMS

DTU Fotonik
Institut for Fotonik

Title:
DronEL - Fast and accurate luminescence imaging of PV installations

EUDP Project number
64019-0603

Project Partners
DTU Fotonik (project coordinator)
Aalborg Universitet
UAV Components
Drone Systems

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Final report

1. Project details

Project title	DronEL - Fast and accurate luminescence imaging of PV installations
File no.	64019-0603
Name of the funding scheme	EUDP
Project managing company / institution	DTU Fotonik
CVR number (central business register)	30060946
Project partners	Aalborg Universitet UAV Components Drone Systems
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2. Summary

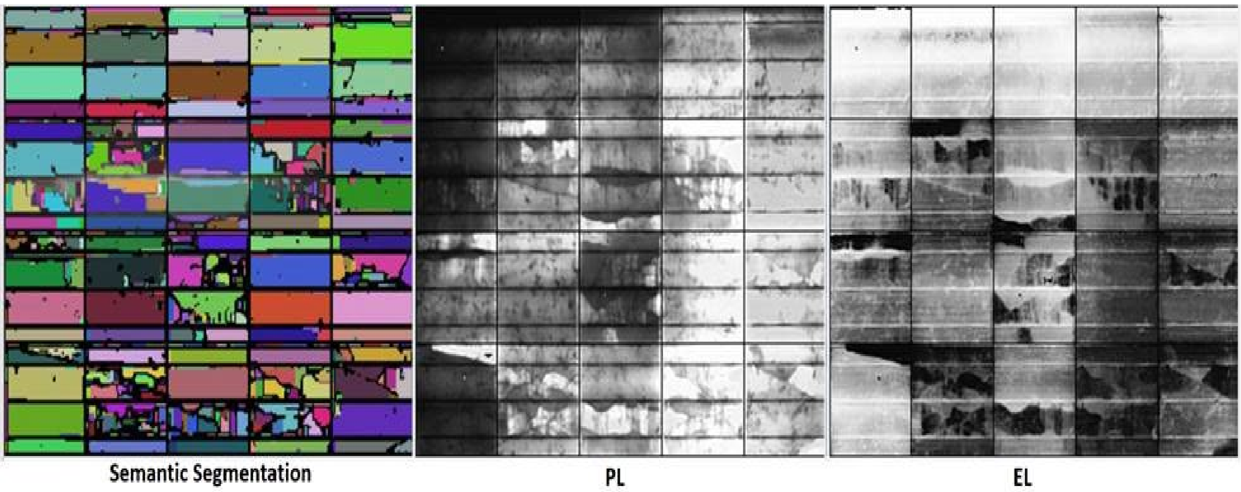
2.1 English summary

The project aimed to further develop and commercialize a drone-based inspection solution that can make preventive troubleshooting on solar cells installed in the field. The project is based on an Innovation Fund Denmark supported Grand Solutions project (2017-2019), where a proof-of-concept of a drone solution that can take high-resolution luminescence images in flight in full sunlight was demonstrated as the first in the world. In this project, this leadership position was utilized to technically mature the developed concept further and bring this to commercialization. The Innovation Fund Denmark Project ended with a proof-of-concept drone (left images below) and the EUDP project aimed to take this into an embedded solution in the form of a gimbal which can go on commercial drones and the result can be seen on the right picture below.

The main activities of the project have been to realize a dedicated technical solution where all the technical units including on-board computer are assembled in a technical configuration in the style of the picture to the right. This unit have both SWIR camera and line laser unit in it and is able to scan across the solar panels and automatically focus and adjust for optimum image quality. The laser line (800 nm) is pulsed, and the induced laser light is absorbed and part of it is re-emitted (1100 nm) where the camera is sensitive, and images are taken in lines and compiled via image processing. By taking multiple images with pulsating light from the laser, these can be subtracted, and sunlight filtered out, so the system works under all weather conditions that allow drone flying (both night and day).

Furthermore, the photovoltaic system wiring need not to be disassembled as the injection of energy comes from the laser carried on the drone. The activities of the project had an iterative character, where hardware and software development took place in several maturation stages, and ended up with a technical solution that, based on machine learning, can automatically identify and classify error types and generate a report.

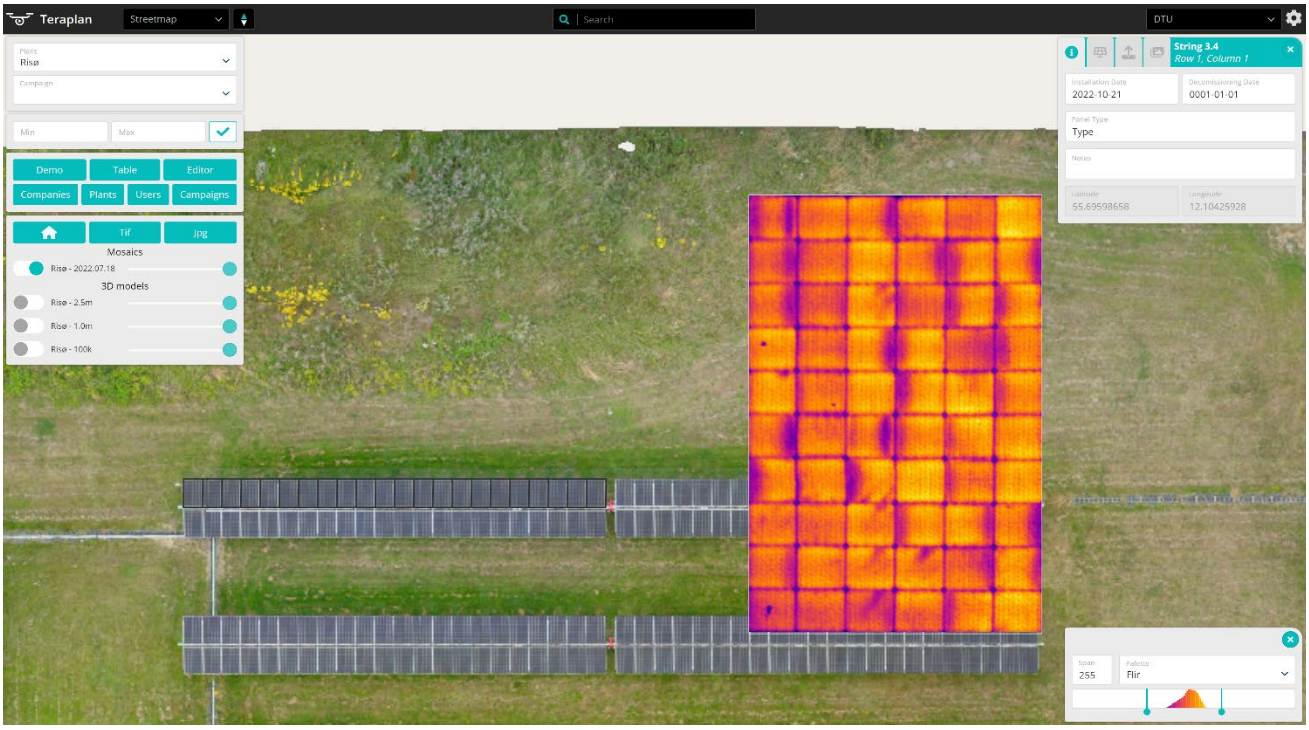
The solution also has third camera installed (RGB camera) for taking normal visual images and for easy navigation before starting the inspection.



Segmentation along with PL and EL extraction of a hand-scanned module as a stress test for the algorithm.

DTU has developed Image processing software to identify faults and categorize into severity which can fit into the reporting software.

Drone Systems TeraPlan back-end have been used to build on top a reporting solution where a solar installation can be virtually constructed from simple drone images and overlayed with the EL inspection images which can be analyzed and report generated automatically with potential actions to take. An example is shown below.



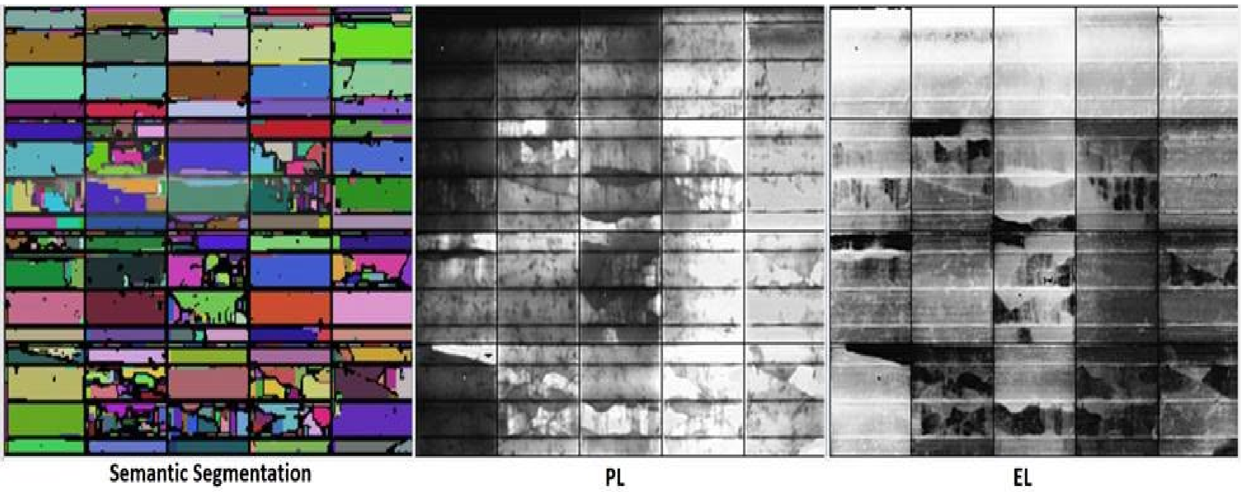
2.2 Danish summary

Projektet havde til formål at videreudvikle og kommercialisere en dronebaseret inspektionsløsning, der kan lave forebyggende fejlfinding på solceller installeret i marken. Projektet er baseret på et Innovationsfond Danmark-støttet Grand Solutions-projekt (2017-2019), hvor et proof-of-concept af en droneløsning, der kan tage højopløselige luminescensbilleder under flyvning i fuldt sollys, blev demonstreret som det første i verden. I dette projekt blev denne lederposition udnyttet til teknisk at modne det udviklede koncept yderligere og bringe dette mod kommercialisering. Innovationsfonden Danmark projektet sluttede med en proof-of-concept drone (venstre billeder nedenfor) og EUDP projektet havde til formål at tage dette ind i en indlejret løsning i form af en gimbal, som kan monteres på kommercielle droner og resultatet kan ses på det højre billede neden for.

Hovedaktiviteterne i projektet har været at realisere en dedikeret teknisk løsning, hvor alle de tekniske enheder inklusive on-board computer er samlet i en teknisk konfiguration som vise på billede til højre. Denne enhed har både SWIR-kamera og linjelaserenhed i sig og er i stand til at scanne på tværs af solpanelerne og automatisk fokusere og justere for optimal billedkvalitet. Laserlinjen (800 nm) pulses, og det inducerede laserlys absorberes og en del af det genudsendes (1100 nm), hvor kameraet er følsomt, og billeder tages i linjer og kompileres via billedbehandling. Ved at tage flere billeder med pulserende lys fra laseren, kan disse trækkes fra, og sollys filtreres fra, så systemet fungerer under alle vejrforhold, der tillader droneflyvning (både nat og dag).

Det særligt attraktive er at solcelleanlæggets ledninger ikke skal adskilles, da injicering af energi kommer fra laseren, der bæres på dronen. Projektets aktiviteter havde en iterativ karakter, hvor hardware- og softwareudvikling foregik i flere modningsfaser, og ender med en teknisk løsning, der med udgangspunkt i maskinlæring automatisk kan identificere og klassificere fejltyper og generere en rapport.

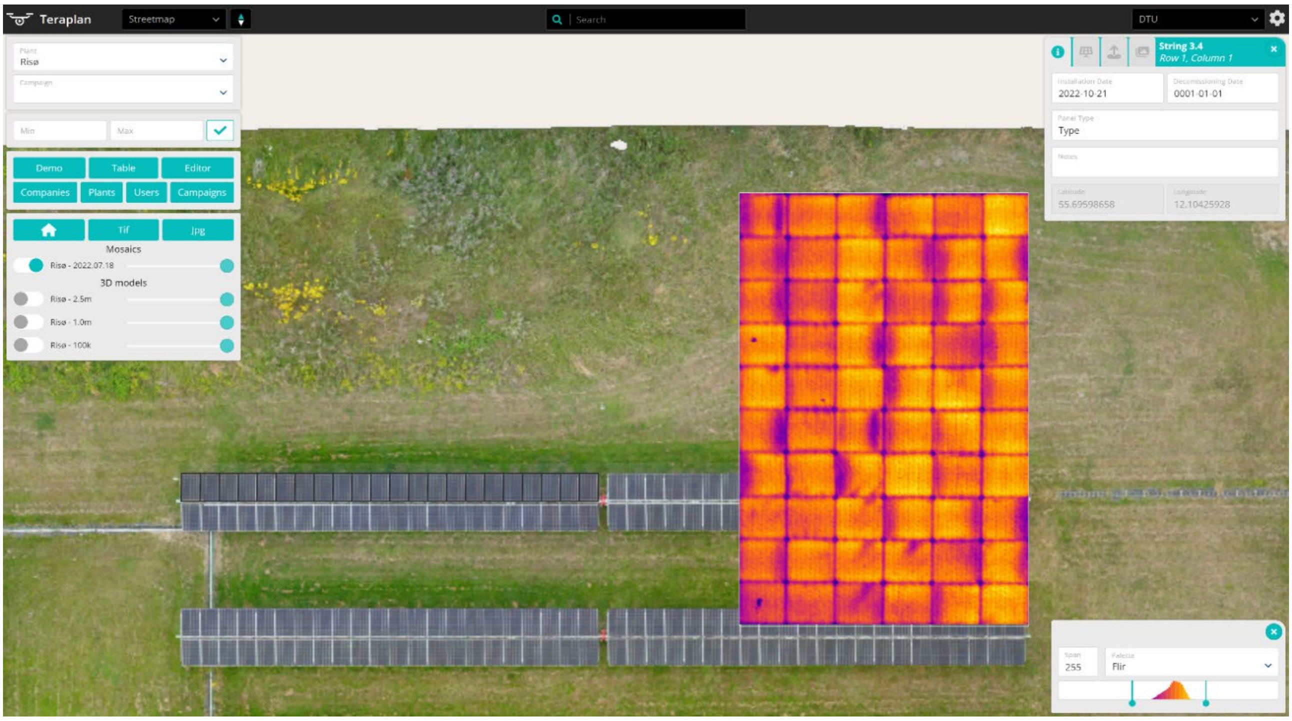
Løsningen har også et tredje kamera installeret (RGB-kamera) til at tage normale visuelle billeder og for nem navigering inden inspektionen påbegyndes.



Segmentering sammen med PL- og EL-ekstraktion af et håndscannet modul som stresstest for algoritmen.

DTU har udviklet billedbehandlingssoftware til at identificere fejl og kategorisere i sværhedsgrad. Billederne passerer gennem denne softwaremotor inden de sendes til apporteringssoftwaren.

Drone Systems TeraPlan back-end er blevet brugt til at bygge ovenpå en rapporteringsløsning, hvor en sol-celleinstallation virtuelt kan konstrueres ud fra simple dronebilleder og overlejres med EL-inspektionsbille-derne, som kan analyseres og genereres automatisk med potentielle handlinger identificeret. Et eksempel er vist nedenfor.



3. Project objectives

The project aimed to further develop and commercialize a drone-based inspection solution that can make preventive troubleshooting on solar cells.

The projected was divided into the following work packages:

- Work Package 1 Project management
- Work Package 2: Payload electrical hardware
- Work Package 3: Embedded software.
- Work Package 4: Mechanical design.
- Work Package 5: Test flights Leader.
- Work Package 6: Image processing.
- Work Package 7: Commercial track.

The Innovation Fund Denmark Project ended with a proof-of-concept drone (left images below) and the EUDP project aimed to take this into an embedded solution in the form of a gimbal which can go on commercial drones and the result can be seen on the right picture below.


Apart from developing the hardware for the tool, also new software had to be made herefore to control the gimbal movement, SWIR camera and laser. Furthermore, wireless control and streaming images to a ground station should be developed for the gimbal. After acquiring the images, the should be processed and stored into a reporting tool which can be used for the end customers to take decisions on e.g. replacing faulty panels.

4. Project implementation

The project was applied for before the COVID-19 pandemic and since 2/3 of the project period was inside this a lot of replanning had to be done to drive the project forward. The commercial partners were very little affected by the pandemic and therefore the work on their sites could proceed more or less as planned. Subcontractors were though much more affected and especially ordering parts from China came with massive delays and the project had to be extended 1 year at some point to ensure to live up to the project goals. The university partners were more affected by the pandemic due to lockdown, tough many of the tasks were image processing and software development, which could be done without access to laboratories. So, all in all the project group managed to navigate very well the pandemic without compromising quality.

The project evolved well as the project group had good chemistry and meet every second week through the whole project for a short status meeting. The project plan was discussed briefly every time and milestones was moved if necessary while other initiatives was taken to help each-others out to meet the goals of the project.

Since the project relied heavily on technology, especially the lack of access to certain microchips became a challenge in the project which gave some unexpected delays. Some could be mitigated since UxV Technologies had a good number of components on stock.

5. Project results

The project aimed to further develop and commercialize a drone-based inspection solution that can make preventive troubleshooting on solar cells. The project is based on an Innovation Fund Denmark supported Grand Solutions project (2017-2019), where a proof-of-concept of a drone solution that can take high-resolution luminescence images in flight in full sunlight was demonstrated as the first in the world. In this project, this leadership was utilized to technically mature the developed concept further and bring this to commercialization. The results are described below.

5.1 Payload electrical hardware

In the project a payload was developed with the purpose to fit on commercial drones. The drone used in the project for test-flights was the DJI MATRICE 600 Pro and the developed prototype solutions therefore was tailored to this platform in the project. A high-level diagram of the developed electrical system is shown below.

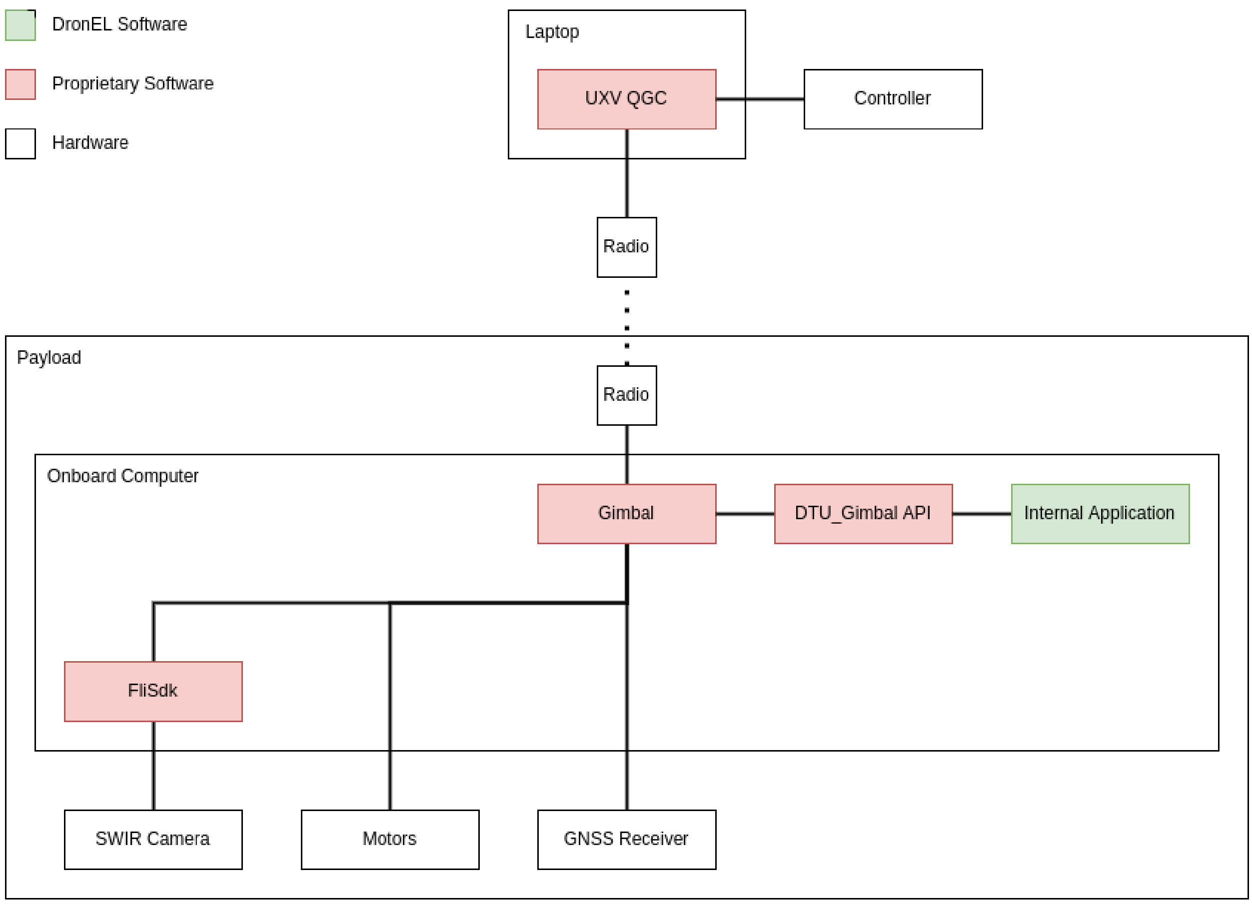


Figure 5.1.1 High level diagram of the hardware developed in the project.

A NVidia Xavier NX is at the heart of the system controlling all the units inside the gimbal. The software for the SWIR camera control is running on it and can therefore control the necessary camera functions and are able to grab the images from it and store it. It controls the motors of the gimbal which can rotate it in 2 axes enabling it to focus the camera on the solar panels and move the laser which will pump photons into the solar cells and the emitted luminescence signal will be captured by the SWIR camera and stitched together before it is analyzed in the end. To be able to control the gimbals orientation from the ground and enable a good video stream to ensure the image quality is sufficient wireless digital data links are implemented in both the gimbal and on the ground station which in the prototype was a laptop computer though in the final product will be a tailored ground station as shown below.

Figure 5.1.2 Gimbal controller which will be tailored to control the DronEL payload.

5.2 Embedded Software

Two software applications to control and operate the payload remotely: the DronePayload APP that runs on the embedded PC inside the payload itself, and the QGround Control APP that runs on a laptop/tablet PC used to control the payload remotely. These two software applications and their main functions are described below.

5.2.1 Drone Payload APP

The Drone Payload APP, depicted in the figure below, is developed in C++ and runs on the NVidia Xavier NX embedded PC, under Ubuntu OS. The application implements the high-level control logic of the payload, interfacing with the payload subcomponents and running the main thread of the application. The app is responsible for: listening for events/command from the remote host controller (payload operator), validating measurement and camera settings received from the host controller, recording high-framerate (up to 320 fps) and high bit-depth resolution (14 bits) EL image frame sequences into multitiff datasets (OPVE datasets), gathering payload status/operational parameters (timestamp, camera framerate, integration time, gain, measurement settings) and compiling them into metadata attached to the OPVE datasets. These functionalities have been implemented based on two software subcomponents, also developed during this project: the Gimbal API and the OPVE multitiff

Moreover, the Drone Payload APP also implements parallel threads for real time processing of the acquired EL image frames, for signal detection and visualisation purposes.

5.2.2 Gimbal API

The Gimbal API is an application interface library that implements the low-level control functions for the FLI CRED 3 SWIR camera and the other drone payload hardware and software components and is used by the

Drone Payload APP to simplify control of these subcomponents. This API was also developed in C++ based on FLI's software development kit (SDK), and UxVs in-house payload control framework, MAVLINK protocol and gstreamer.

The main functions implemented in the API are: acquiring live image frames from the camera, encoding and streaming them to the host PC (QGround Control app), decoding MAVLINK data messages received from the host PC and passing them to the Drone Payload APP, receiving telemetry data from the drone flight controller, setting/getting camera frame-rate, integration time and gain, recording and timestamping EL images into an internal circular buffer, recording EL images sequences into low resolution (8-bit) AVI files.

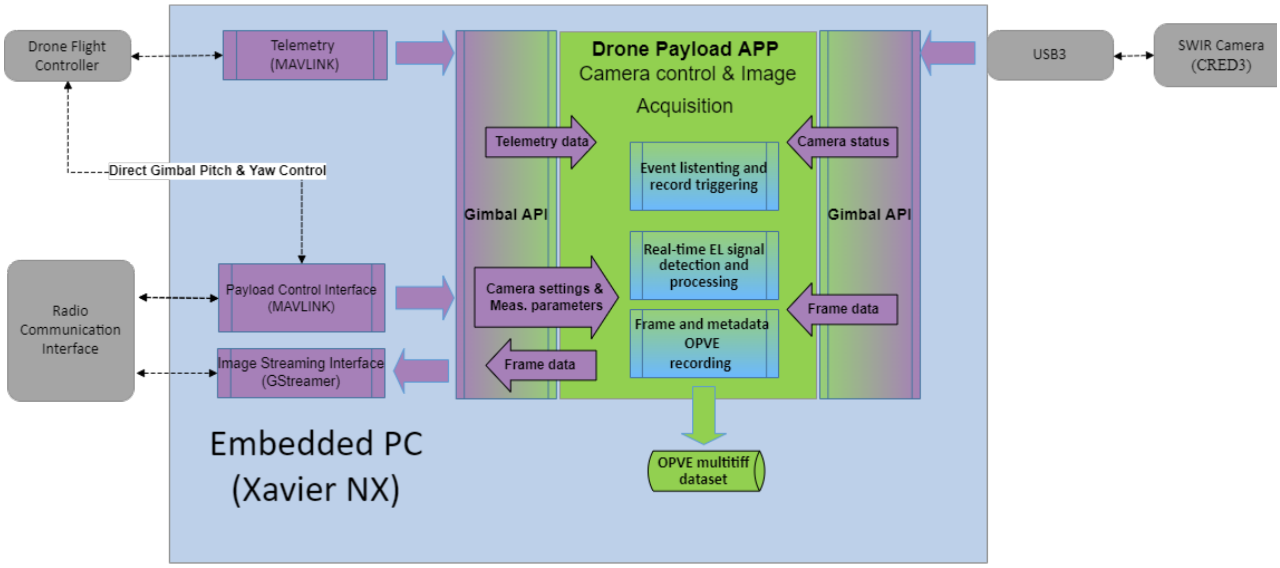


Figure 5.2.1 Concept diagram of the software running on the embedded drone payload PC

5.2.3 OPVE multitiff

One particular challenge for drone based EL image inspection of PV modules during daylight, is that a high number of EL images of the same PV module/scene must be acquired in a short period (200-300 frames per second) with a relatively high bit-depth resolution (14 bits) and lossless storage, however conventional video formats are limited to 8 bits. In addition, for each module/scene measurement, the camera and measurement settings, as well as drone and panel position need to be recorded together with the EL image sequences, to facilitate post-processing and panel identification. Therefore, we developed the Open PV Environment (OPVE) Tiff format, inspired from the Open Microscopy Environment format, along with the necessary API functions, that can store high bit-depth tiff image sequences into single multi-tiff file, corresponding to a module/scene measurement, as well as attach JSON encoded metadata, corresponding to the camera and measurement settings.

The resulting OPVE measurement datasets are stored on the embedded PC during recording and transferred post-flight on a PC for post-processing and reporting of the measurements.

5.2.4 QGround Control APP

To control the drone payload parameters, recording, and live visualisation of the camera video during flight, a ground station application is necessary that runs on a remote host PC (laptop, tablet) and communicates with the drone payload through radio. Such a ground station application was developed based on the QGround-Control (QGC) open source software - which was modified based on the requirements of this project. Some of the modifications and functions implemented are live video streaming of SWIR/EL images, configuring the camera (frame rate, gain, exposure) and measurement settings (PV string/table ids, modulation parameters) from the host PC, enabling/disabling the payload motors, triggering the recording, as well as controlling the payload pan and tilt using a joystick controller.

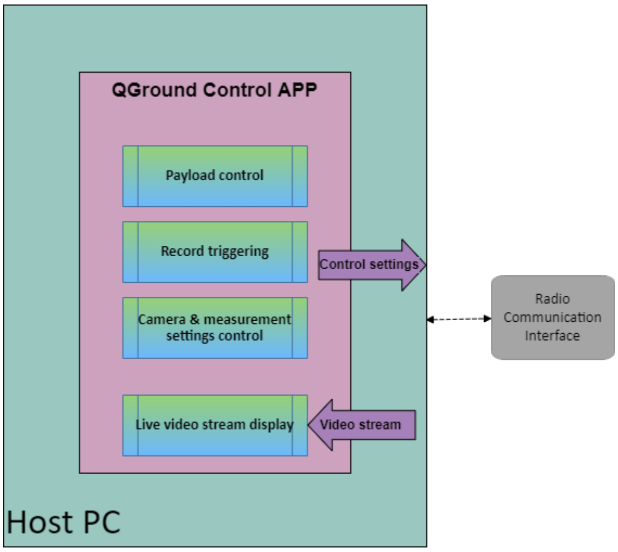


Figure 5.5.2 Concept diagram of the QGround Control software running on the host PC

Figure 5.5.3 QGround Control APP graphical user interface for live video streaming and control of the drone payload.

5.3 Mechanical Design

The mechanical design of the gimbal was made in SolidWorks and produced in aluminum by subcontractors. The rather large round housing was though made in 3D printed polymer since it had to be tweaked and fitted with wires and other components that required mechanical adaptation which would be much harder to do in aluminum. The final product will have all its components made in aluminum.

Figure 5.3.1 – Mechanical drawings and rendering of the developed DronEL payload.

Above a rendering is shown of the assembly file with all the units mounted inside the gimbal. The finalized version implemented on the drone is shown on the photos below.

Figure 5.3.2 – Photos of the developed DronEL payload.

5.4 Laboratory tests

Electroluminescence (EL) and Light Induced Luminescence (LIL) are the main luminescence techniques that we focused on to develop in this project.

5.4.1 Electroluminescence

EL, as a laboratory test technique of PV diagnosis, is well established and our tests were centered in camera calibration for high quality of the images when in a high noise environment, (such as sunlight and motion conditions) i.e., daylight drone inspections. The calibrated camera results for EL are shown in Section 5.6.

5.4.2 Light Induced Luminescence

The LIL technique is a fully contactless luminescence imaging method with potential to overcome field inspection drawbacks faced by EL imaging. On the other hand, LIL is a new technique that even for indoor applications is not well established and requires extensive development and optimization. The carrier injection location characteristic of LIL can provide particularly different mapping of cell-isolated areas due to cracks. Our first tests were carried out to evaluate how the luminescence signal of electrically isolated regions in the PV cell with different levels of severity perform in the LIL characterization method.

Figure 5.4.1 illustrates the setup used for LIL image acquisition. The luminescence images under low natural light were acquired using as excitation source an 808 nm laser diode at four different optical power intensities. The laser source was placed at 152 cm from the sample with 5 W optical power, what corresponds to an intensity of about 3.2 Suns at the illuminated area. An angular scan of the laser line beam was performed over the region of interest with the use of a robot arm that rotated the laser at 2 degrees per second. The camera was kept fixed in its position at 124 cm from the sample. The images were acquired with a fixed 30 ms exposure time and to cut out the laser emission, a 950 nm long-pass filter was placed in front of the lens.

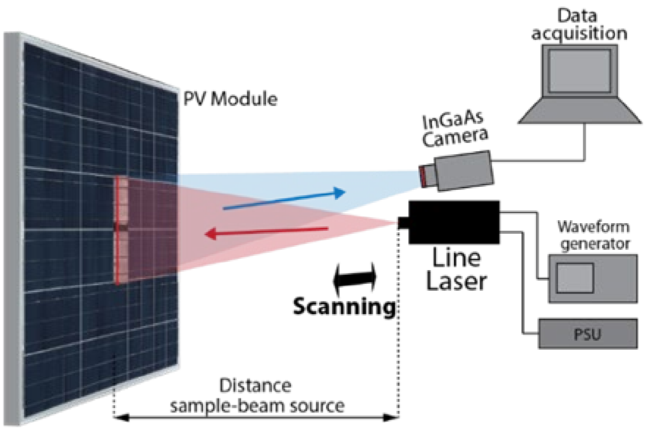


Figure 5.4.1 - LIL setup

Figures 5.4.2 and 3 show one cell of a single image from an LIL scan sequence and its correspondent surface plot. Figure 5.4.2 has the laser beam perpendicular to the busbars and Figure 5.4.3 parallel to the busbars. The whole cell can be observed in both cases, due to a contactless EL signal generated by the lateral currents induced by the laser light. The laser beam orientation on the isolated crack area had very noticeable influence on the inner crack luminescence signal. With the laser line perpendicular to the busbars, the laser beam is also perpendicular to the general crack area shape that is often parallel to the busbars. In this case, the laser peak (photoluminescence – PL - signal) has a higher signal on the cracked area, and the contactless EL presented a slightly higher signal in the isolated crack area.

With the laser line parallel to the busbars, more light hits the isolated area and its luminescence signal presented a well distinguishable intermediate level in relation to the laser peak and the entire cell, observable in the surface plot. This occurred because of the lateral currents that could not dissipate to the entire cell due to the high series resistance of the cracks.

Figure 5.4.4 shows the constructed images from an LIL scan at 50% excitation intensity in both scan orientations. The image processing in this case stacks the sequence of images with the beam line at different position over the cells into one overlapped image. This means that what we see is the contactless EL from healthy and cracked areas all overlapped and normalised by the highest luminescence intensity value. Cracked areas and finger failures have higher or lower luminescence signal due to crack/laser orientation. In the horizontal scan (Figure 5.4.4, top), the laser beam was perpendicular to the busbars, but was parallel to the grid fingers. In the several isolated areas (including Crack C – red arrow), the affected (broken) fingers appear with high relative luminescence signal due to the laser beam orientation. On the other hand, in the vertical scan, Crack C is the only isolated area that is predominantly highlighted due to the laser beam orientation. Regions with Crack B (orange arrows) and A (green arrow) remained relatively unchanged in relation to the scan orientation. A healthy and well-connected cell area (blue arrow) preserved the same diagnosis information as well for both scanning orientations, with differences in the luminescence intensity just due to the intensity normalisation.

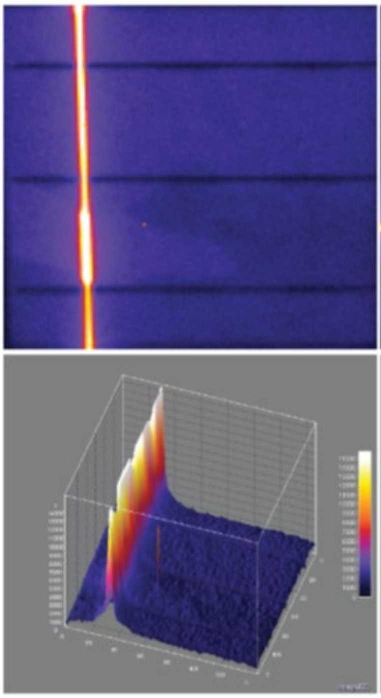


Figure 5.4.2 - Laser-line perpendicular to the busbars: One frame of an LIL image scan sequence (top) and its correspondent surface plot (bottom).

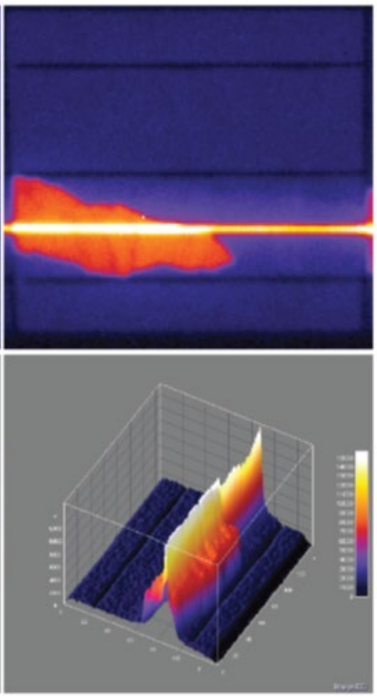


Figure 5.4.3 - Laser-line parallel to the busbars: One frame of an LIL image scan sequence (top) and its correspondent surface plot (bottom).

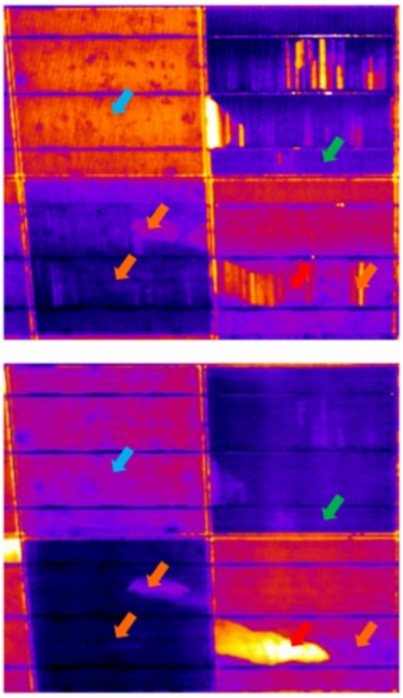


Figure 5.4.4 - LIL standard deviation of the horizontal (top) and vertical (bottom) scan orientations at 50% of laser power intensity.

To better understand how LIL can characterise cell cracks and to explore the highest potential of collecting EL and PL signal at the same time, we performed tests with monocrystalline cells, which don't present crystallography defects in the EL images, as saw with multicrystalline cells in Figures 5.4.2 to 4. Since the carrier injection location characteristic of LIL can provide particularly different mapping of cell-isolated areas due to cracks than conventional EL imaging, we aim to characterise the differences between the two. To achieve this, we analyse the luminescence signal of a healthy and a cracked cell in a single frame of an LIL scan, comparing differences between connected and disconnected areas of the broken cell.

In the representation of Figure 5.4.5, two single frames of an LIL scan are shown side-by-side for more direct comparison of a healthy (cell to the left) and a damaged (cell the right) PV cell. On the left part of Figure 5.4.5, the frames with two different laser positions can be seem in triplicate to show the line profile in three different positions – Profile 1 at the top, Profile 2 in the middle and Profile 3 in the bottom. The luminescence intensity profiles to the right show, at the same scale:

a) A peak where the laser beam is positioned (PL);
b) A baseline contactless EL in the entire healthy cell area and in the connected areas of the damaged cell;
c) A bright isolated area on the part of the damaged cell (highlighted contactless EL) where the laser beam is located;
d) An increased peak intensity of the PL signal on the highlighted isolated area;
e) Dark isolated areas on the part of the damaged cell where the laser beam is not located.

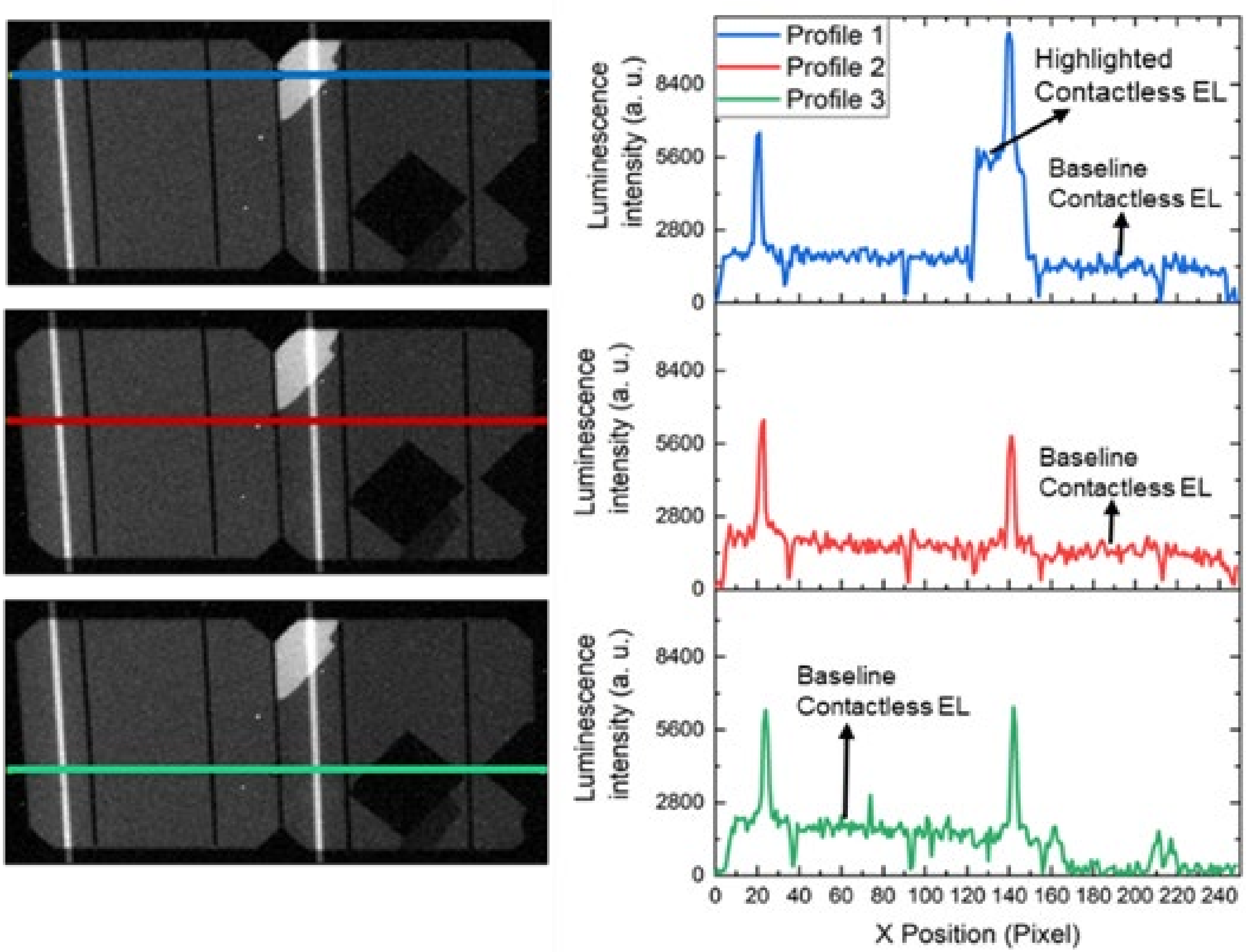


Figure 5.4.5 - Profile plots of two side-by-side single frames of an LIL scan. Left: line profile in three different positions – Profile 1 at the top, Profile 2 in the middle and Profile 3 in the bottom; Right: luminescence intensity profiles (here shown as gray values arbitrary units).

The sequence of images acquired contain partial luminescence data for cells/regions of the module and have to be stacked and reconstructed into a complete module luminescence image. Using the known input of module size and matrix configuration, this is done by identifying the beam position and segmenting it for its removal, stacking the luminescence signal of the image sequences acquired and averaging to eliminate noise. After this step, two images are obtained, labelled as “Highlighted Contactless EL” and “Baseline Contactless EL”. The highlighted contactless EL image aggregates the high luminescence intensity provided by electrically isolated areas when the laser beam scans over them (see Profile 1 in Figure 5.4.5). In contrast, the baseline contactless EL image aggregates the luminescence when the laser scans over electrically connected areas, resulting in a luminescence image more similar to conventional EL. The PL part of the scan is not used for building an output image at this stage. A new laser source was built later in the project to address this drawback.

Figure 5.4.6 shows the results of reconstructed images from the LIL scan compared with conventional EL measured at 100% and 10% short circuit current (Isc) bias excitation. Qualitatively, the diagnosis of the isolated areas is correspondent to 100% Isc. However, for this configuration and image reconstruction, the LIL does not detect any of the finger disconnections, visible in the conventional EL 100% Isc image.

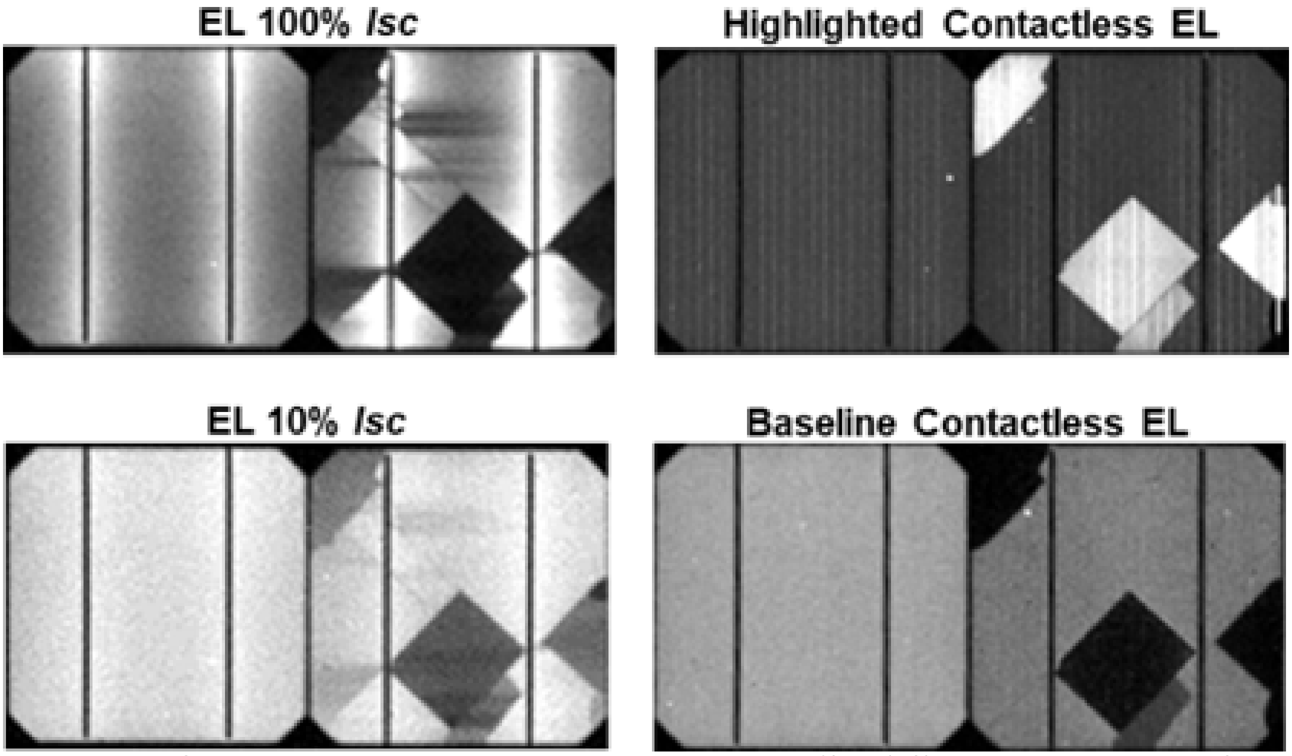


Figure 5.4.6 - Comparison between conventional EL images at 10 and 100% Isc (left) and reconstructed images from LIL scan (right).

Considering a frame of LIL scan with the laser positioned close to one cell such that the entire beam hits the cell, and the full laser intensity is converted into luminescence in the PV cell, a luminescence intensity comparison is made with traditional EL images. In the top of Figure 5.4.7, the EL (left) and the LIL (right) images can be seen, where the correspondent EL image has the current bias that match the luminescence intensity of the Baseline Contactless EL from the LIL image. This match can be verified in the profile plots in the bottom of Figure 5.4.7. The match occurs at 13% of Isc current bias of contact EL. In these images, the camera settings were identical.

When different laser intensities are used, we observe a linear dependence of the Baseline Contactless EL signal with the laser intensity range available, as shown in the match with contact EL, in the inset graph of Figure 5.4.8. When extrapolating this apparent linear dependency (Figure 5.4.8), we have the indication that a laser power of 48.5 W illuminating a single PV cell will generate a contactless EL image as intense as a contact EL with 100% Isc. This is a relatively high-power laser and, with a collimated beam, can possibly provoke burns in some PV components.

A diffuse beam, however, will minimise the potential damage to the cell and make use of the PL part of an LIL scan – we take these factors in consideration in the construction of a new laser prototype later in the project. The higher intensity presented by the reconstructed images and particularly by isolated cracks, however, indicates that one of the most significant faults observed via luminescence imaging - C mode cracks - will require less laser intensity than that to be easily detectable outdoors. In this case, the ambient conditions during the LIL scan must be observed.

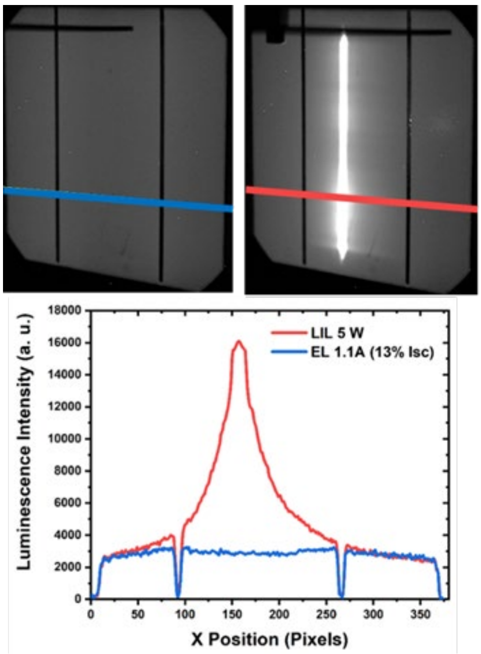


Figure 5.4.7 - LIL single image (top right) compared with contact EL (top left), and profiles (bottom) of the blue and red lines indicated in the images on top.

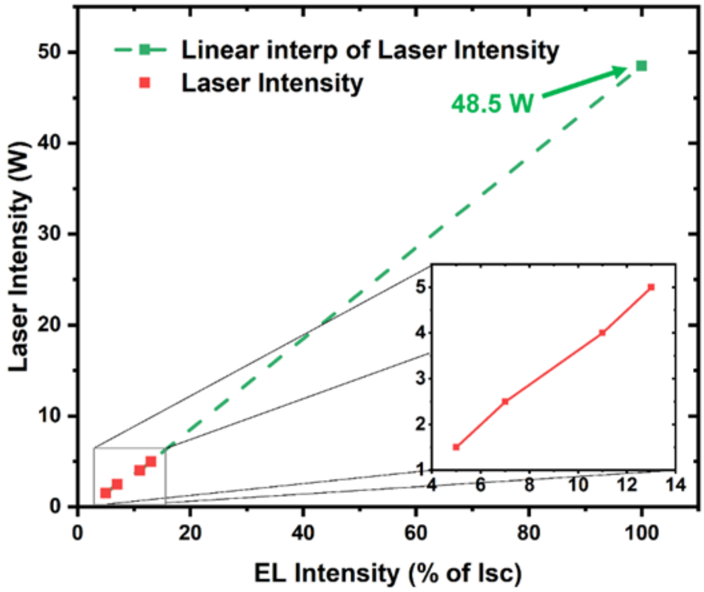


Figure 5.4.8 - Laser intensity match with contact EL current bias in % of Isc.

5.4.3 LIL under Sunlight environment

Additionally, we demonstrate how LIL imaging can be performed outdoors during daytime. For sun irradiances above approximately 100 W/m^2, it is indicated that EL imaging reaches a limit in being performed with cameras that required long exposure (cameras with Si-based sensors). For InGaAs cameras, full daylight EL imaging is possible using electrical signal modulation and sunlight noise filtering via background image subtraction. This is reported for 100% Isc EL signals. In Figure 5.4.9, a single image LIL is acquired under low daylight irradiance (approximately 2 W/m^2) with 20 ms exposure time. For a 5 W laser, this level of ambient noise was enough to fade considerably the luminescence signal, requiring background subtraction. As the LIL image is obtained successfully with background subtraction, it is expected that, for higher luminescence intensities, the same strategy used for contact EL could be used. In the LIL case, the modulation can be performed still contactless, controlling the laser duty cycle, and synchronising it with the camera during image acquisition while the PV panels are in open circuit.

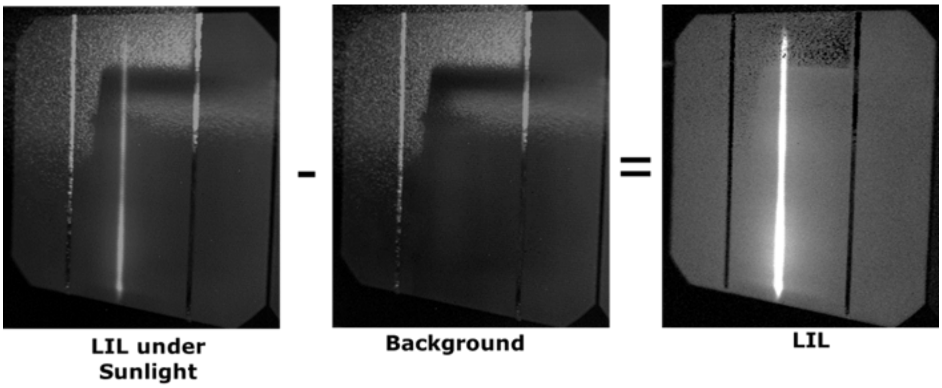


Figure 5.4.9 - Single frame LIL under sunlight at app. 2 W/m^2 with subtracted background.

Following these results, we designed a new laser module with high power, enough to cover each illuminated cell with approximately 48 W of optical power with a diffuse beam shape. With efficient image processing, this way, contactless EL and PL images will be available for reconstruction and ultimately PV diagnosis.

5.5 Outdoor tests and Test Flights

In order to carry out the test flights with the drone payload to do EL inspections, a guide was developed by DTU in order to optimise the diagnosis of outdoor luminescence inspections.

The camera hardware requirements for outdoor EL inspection are an InGaAs camera with a SWIR lens and a bandpass filter that blocks all visible spectrum of light and which transmission occurs around the c-Si luminescence peak, between 1111 and 1162nm.

Daylight EL imaging requires a current injection device capable of applying current to a module or a series of modules. A current injecting device such as a power supply has been used. The power supply must be able to modulate the current of the DUT and supply the required voltage and must be able to reach Isc in the peak of modulation. Different waveforms can be applied to modulate the current of the DUT. The waveform shape and its frequency need to be chosen based on the image processing strategy, considering a low frequency will lead to problems with fast irradiance changes. Due to daylight conditions, current will be generated in the modules and flow back to the power supply, therefore, the power supply must be able to act as a load, so a bidirectional power supply is therefore required. Due to the PV farm string requirements a 15kW power supply was used.

In Figure 5.5.1, a test flight using the drone payload with the camera integrated is shown. The flight was carried out at DTU Risø PV farm. For the flight a minimum of two operators are needed, one to pilot the drone and another one to move the payload and record the images. Prior to the flight, the appropriate electrical connection of the power supply to the PV string needs to be done. EL images recorded with the drone have to be processed after the flight. Images results and their processing are presented in the following section, for what tracking and image stabilisation and reconstruction is needed.

Figure 5.5.1 - Daylight drone during flight tests imaging Risø's PV farm. One operator is needed for the drone control and another one to control the image acquisition, the payload and the PV string modulation.

Regarding LIL inspection, following the conclusions of the lab test, a more powerful laser was developed and tested. In order not to damage the module´s components a diffuse beam laser has been used, and since approximately a power of 50W per PV cell was required, the laser power was increased to 150W, aiming to cover the area of three cells when scanning the modules. Figure 5.5.2 shows a frame of an indoor scan of a PV module with this new laser; as required the region where the laser is more powerful is covering three cells.

Figure 5.5.2 - Image frame of the laser scanning a PV module. Three cells are covered by the laser´s high power region.

The proof of concept laser pack consists of the laser, a driver to power it, a battery pack, a heatsink to dissipate the heat during operation and a fan to cool it down. The pulsed laser is synchronised with the camera frame rate, which acts as a trigger. The laser was mounted on a scanning head to reproduce the drone payload integration and continue the development from the ground. Figure 5.5.3 shows the described laser pack mounted together.

Figure 5.5.4 shows the laser pack mounted on the rotating scanning head. The last iteration of the prototype includes the camera in the scanning head in order to completely reproduce how the laser scans look like in the drone payload.

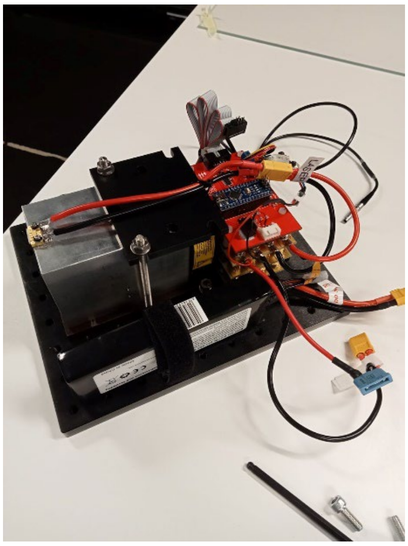


Figure 5.5.3 - Laser setup for testing consists of the laser, battery, drivers and heat sink.

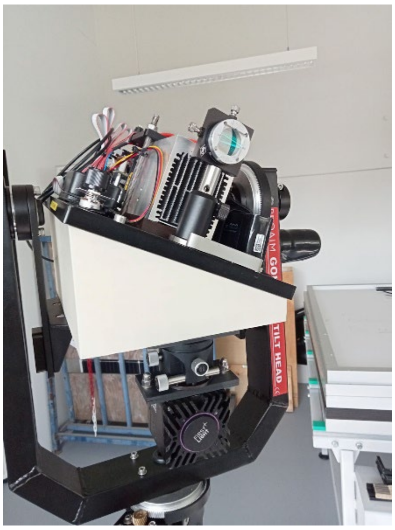


Figure 5.5.4 - Laser setup mounted on scanning head for drone payload testing.

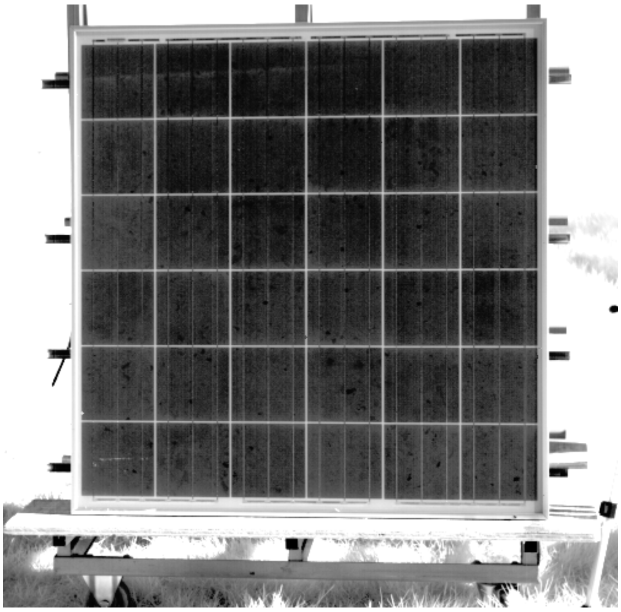


Figure 5.5.5 - Laser scan of a PV module in daylight. The laser line is on the top-left 3 cells of the module.

Figure 5.5.5 shows a PV module being scanned outdoors with the laser setup developed. The laser line in daylight is harder to see due to the ambient light noise. The laser was placed at a distance of 4 to 5 meters from the module, covering three cells in the scan. That distance between module and laser is the required one for a safe drone flight.

Results of laser scanning were satisfactory for POA irradiances between 0 to 400 W/m^2, therefore scans during nighttime, overcast days and slightly sunny days are possible. Results of processed images are shown in the next section.

5.6 Image Processing

DTU Fotonik has developed a generic algorithm for extracting photo- and electroluminescence data from a series of Laser Induced Luminescence images. It does not rely on any particular shape or orientation of the laser beam, but knowing the laser characteristics can improve accuracy. It has been shown to work even with a completely manual scanning with the laser across the panel.

The algorithm works by analysing and collecting statistical data based on the response-characteristics of reference points as the laser passes over the PV cells.

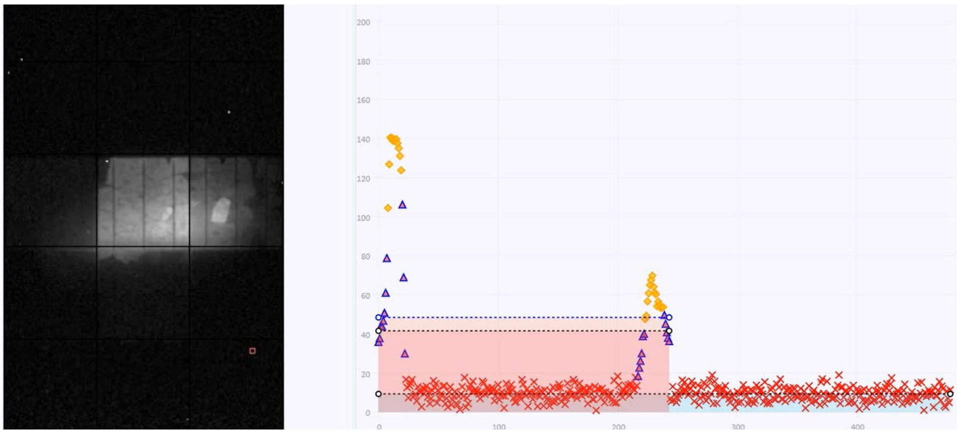


Figure 5.6.1 As a laser passes over a reference point on a PV module, cracked areas will have distinct luminescence responses, which can be used as “fingerprints” to cluster connected pixels.

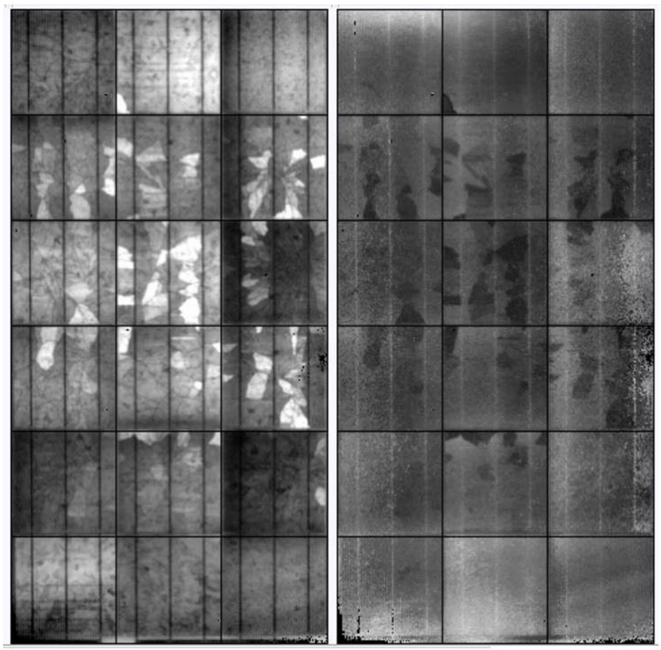


Figure 5.6.2 PL (left) and EL (right) images extracted from an LIL image series taken during daylight (single pass).

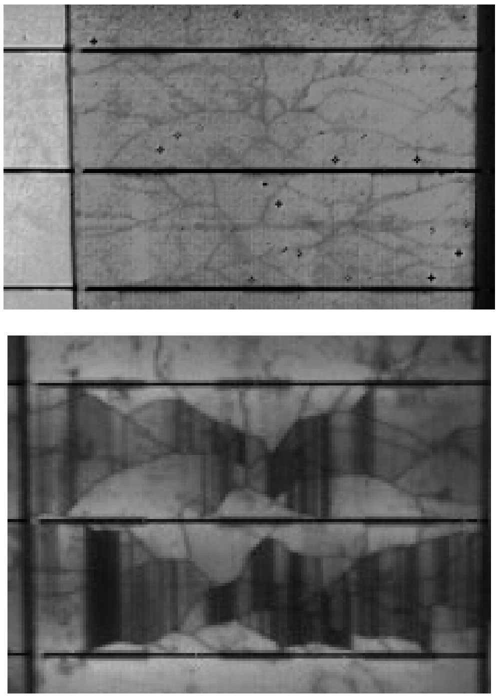


Figure 5.6.3 Top: Isolation of line-cracks and minor defects using LIL data. Bottom: EL reference image.

The data collected by the algorithm can be transformed into different types of information about the cell, including PL and EL, but it can also provide advanced feature extraction, such as enhancement of line cracks as seen in the previous figures. This cannot be done with regular EL analysis.

Additionally, this "luminescent fingerprint" principle has been applied in a segmentation algorithm capable of clustering areas with similar fingerprints, so that specific data from each individual area - be it cracked or healthy - can be extracted.

Figure 5.6.4
Left: Segmentation of one of two cells into distinct regions of similar luminescence fingerprints. Part of the laser spot can be seen in the left cell.
Right: PL data of the same cell extracted from LIL data. As can be seen, the algorithms have situational awareness which assists in avoiding improper clustering between cells.

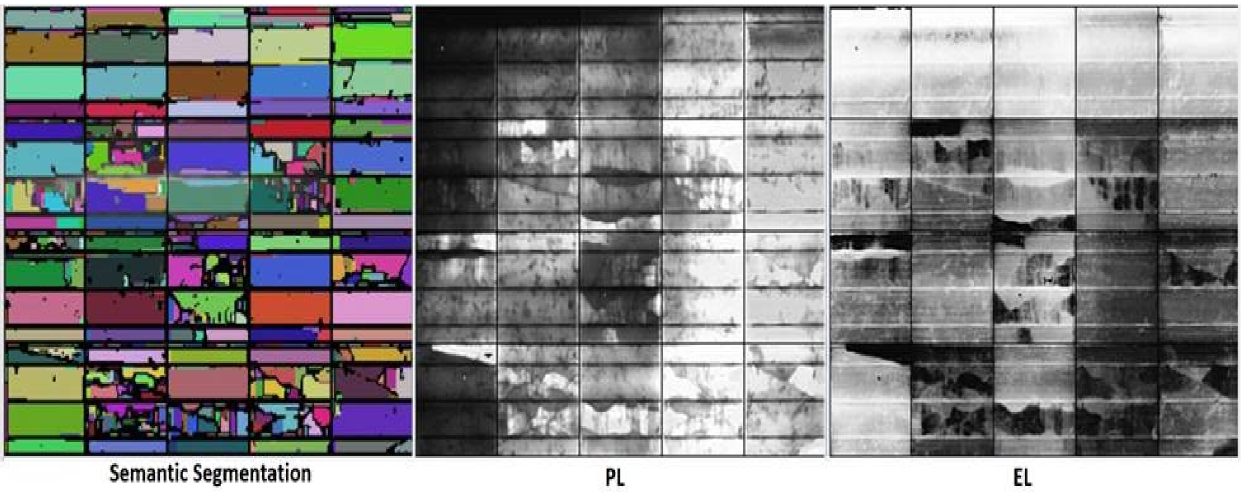


Figure 5.6.5 Segmentation along with PL and EL extraction of a hand-scanned module as a stress test for the algorithm.

In order for drone-based scanning - or motion based scanning in general - to be feasible, the PV modules and individual cells must be highly stabilized, so that the LIL response of individual reference points on a cell can be tracked reliably. This is not possible if the position of the reference point in the image series keeps changing even the slightest. By stabilizing and correcting the captured PV module into a rectangular frame, each pixel in the resulting image becomes a reference point for the analysis algorithm.

To fulfil this requirement, DTU has developed an algorithm that can track a panel with sub-pixel accuracy, using special anchor-features that are particular to each distinct PV-module type. This allows for stabilization beyond what can be achieved through regular image-feature algorithms.

To perfect the algorithm, it has been tested on a number of modulated electroluminescence image series acquired by the drone payload and other types of movement. This strategy was chosen because modulated EL analysis has a straightforward relationship between SNR and image quality, and the resulting images can be easily validated with data acquired with a stationary camera.

One example from the many motion-based stress-tests of the tracking algorithm can be seen in the following.

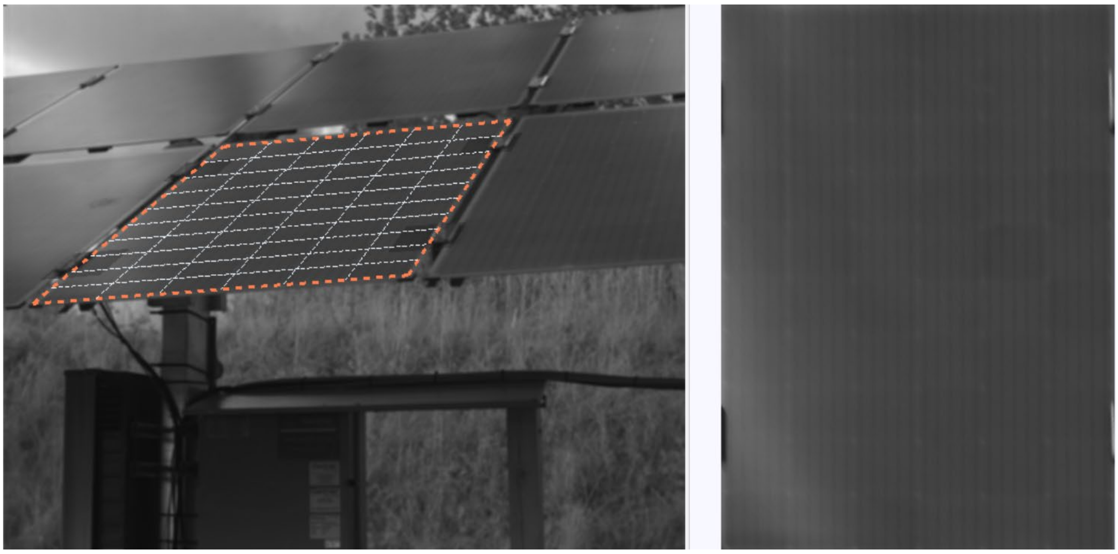


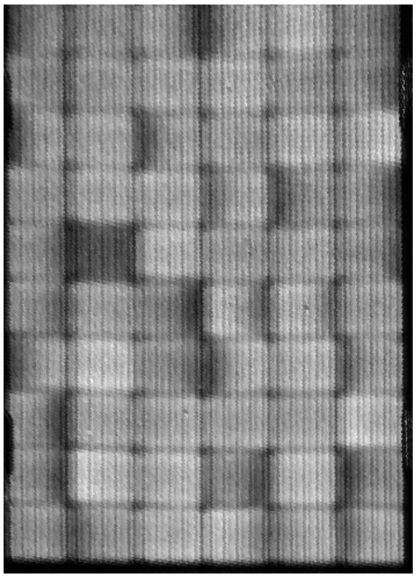
Figure 5.6.6

Left: A screenshot with an annotated tracking frame, from a low-angle motion-based acquisition using the drone payload. The tracking algorithm can track panels with acute precision even from problematic angles, using anchor features that can be tailored to a given module type and even mounting system.

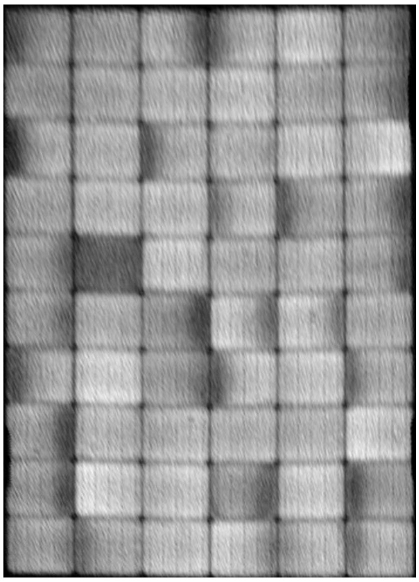
Right: A corrected view of the tracking frame, where no EL information can be gathered.

The following images demonstrate how the tracking algorithm can reconstruct an EL image even from this difficult angle with a seemingly almost featureless panel. A better viewing angle improves the quality of the stabilized image, but both the precision of the stabilization algorithm and its impact on the image quality is easier to demonstrate from a worst-case perspective.

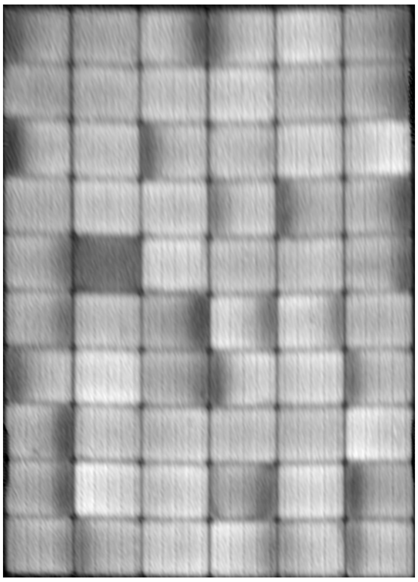
a) shows a non-stabilized analysis. b) shows a regular analysis with precise tracking/stabilization. c) shows a stabilised analysis, where aliasing caused by the camera movement is taken into account in the time-domain. This makes it capable of not only anti-aliasing but also upscaling the detail level beyond the available camera resolution.



a) EL analysis without proper tracking.



b) EL analysis with tracking



c) EL analysis with anti-aliased tracking.

5.7 Reporting Platform

In order to organize, visualize and facilitate easy exploitation of results a prototype reporting platform has been developed by extending the Teraplan web platform.

The overall architecture is shown in the diagram below. The backend is responsible for storing and manipulating data by exposing endpoints for uploading, creating, editing, etc. The frontend is responsible for visualization as well as interacting with the data by utilizing the backend endpoints.

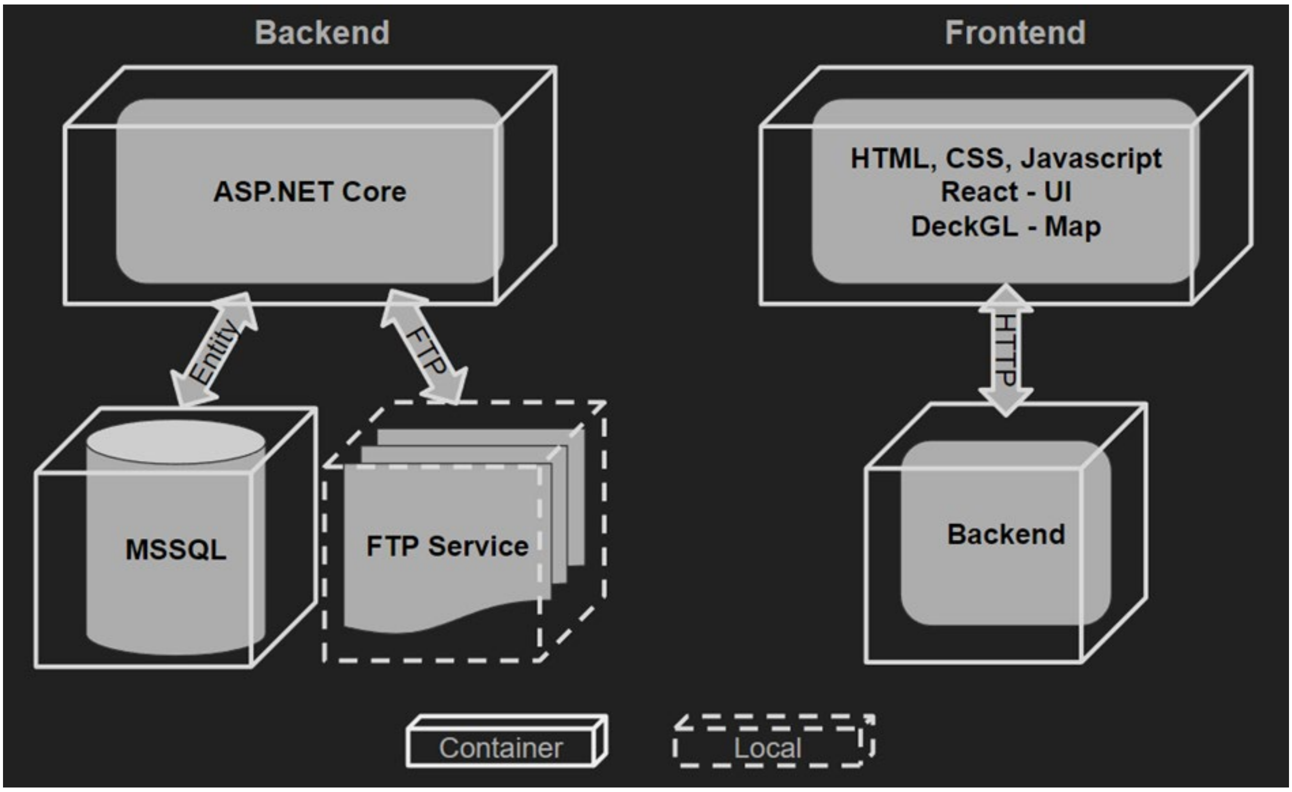
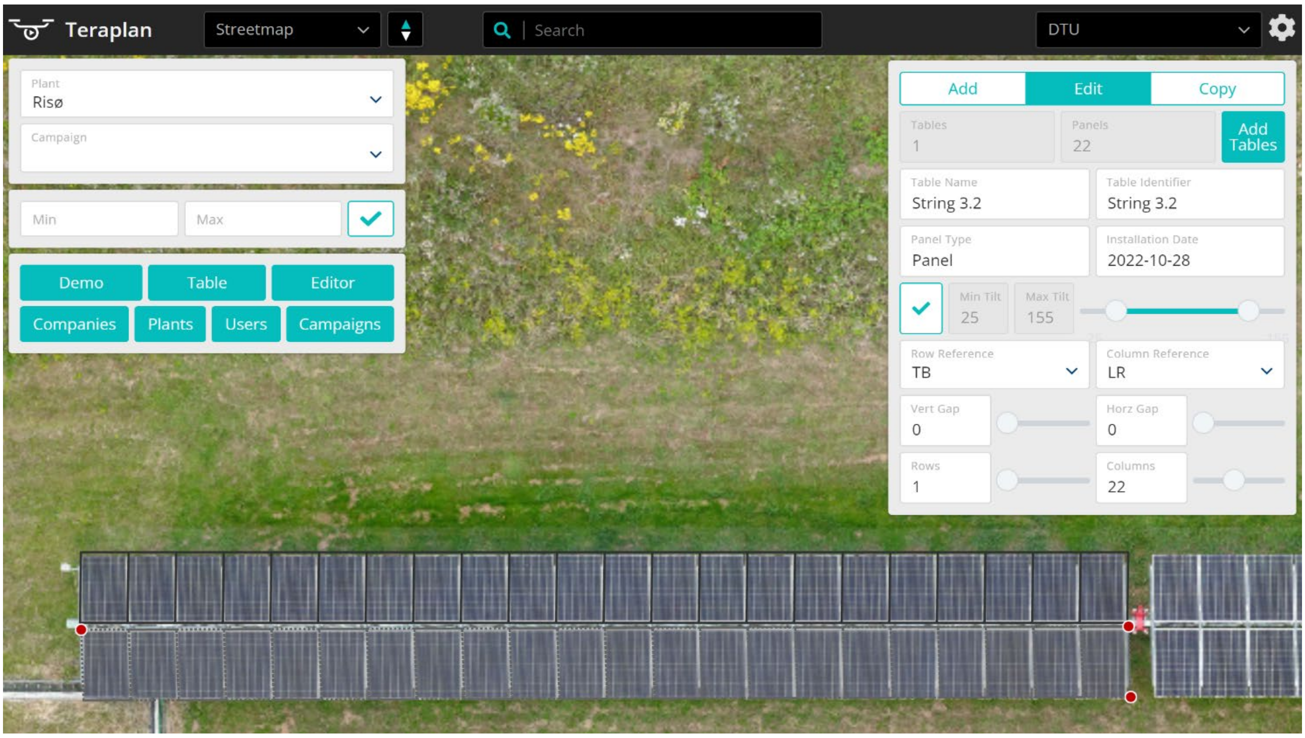


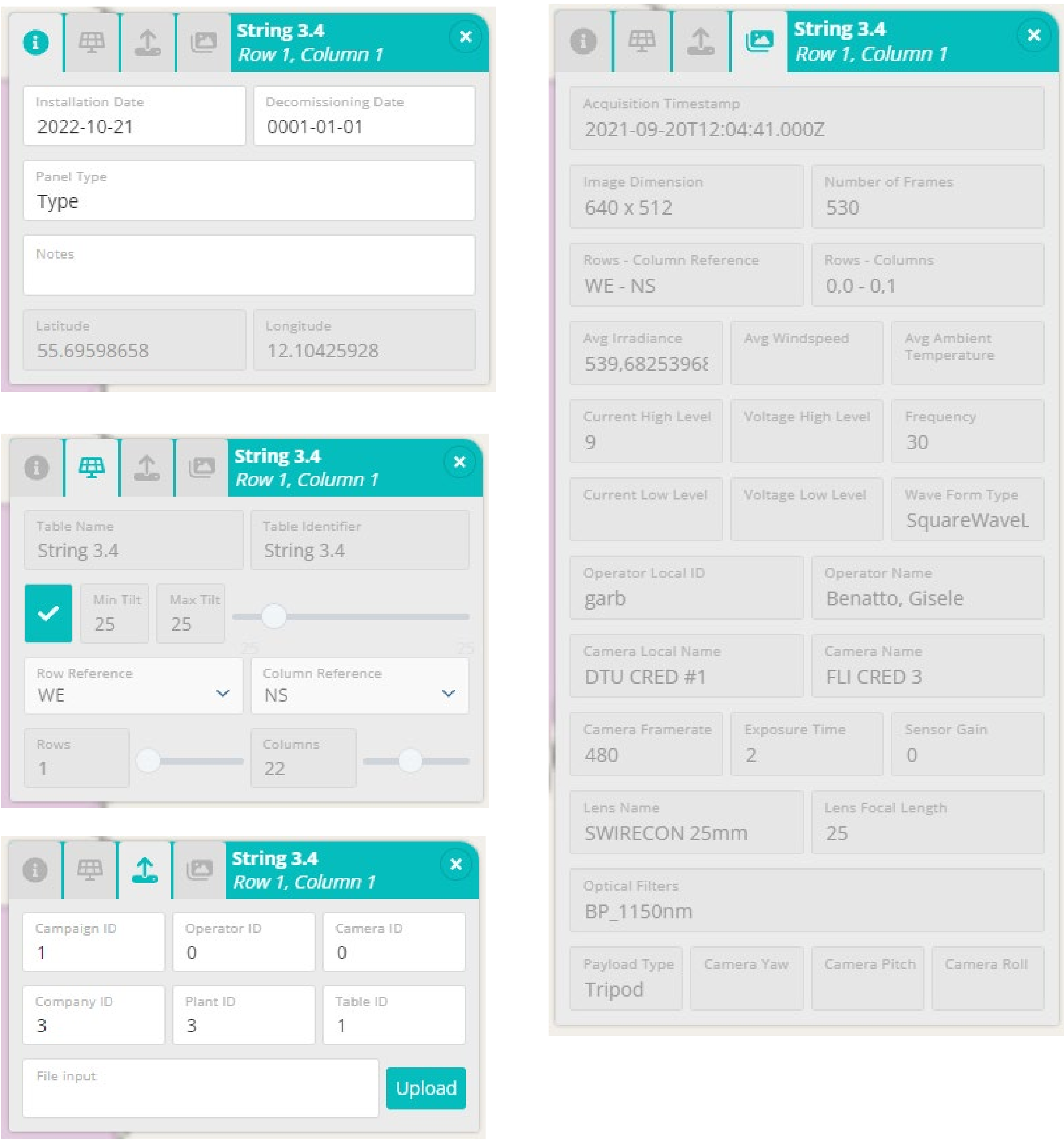
Figure 5.7.1 Diagram of technologies used along with communication arrows for both backend and frontend. Docker was used for containerization.

The backend is implemented in C# using the ASP.NET Core library for HTTP communication along with the Entity Framework which facilitates the database connection and object mapping. The frontend is based on standard web technologies such as HTML, CSS and JavaScript, built with the React UI library. Mapping capabilities are implemented using the deck.gl library to ensure the platform has a GIS familiar feeling. All components are deployed in docker containers to establish dependency isolation and provide easy scalability.

Overview of the frontend application. The left-hand side contains all controls regarding what is shown on the map, while the right-hand side contains information regarding the active panel. An image of the active panel is shown in a floating frame on top of the map.



Close up showing the process of adding a new table to the plant. Three table corners are marked on the map and the required information added to the UI element on the right. Tables can be edited and duplicated to facilitate rapid definition of an entire plant.



The collection of images above shows the contents of each tab element on the right-hand side (active panel). The first tab contains general panel information. The second tab contains information about the active panel position. The third tab allows for uploading captured data to the platform. The fourth tab contains information about uploaded data.

5.7 Dissemination

The project has led to the following disseminations:

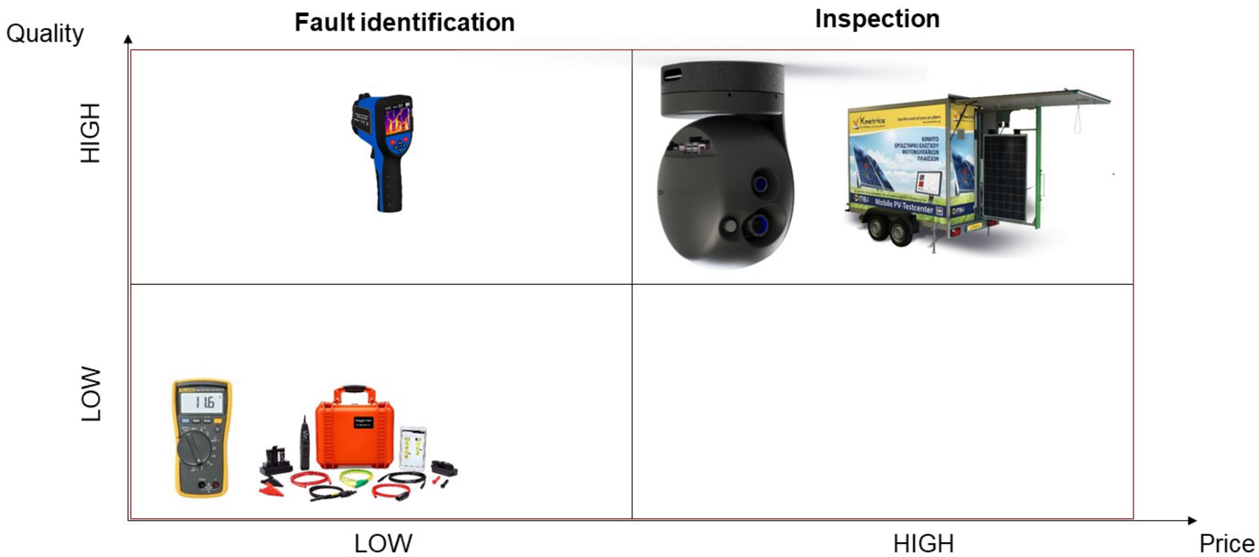
1. Mantel, C, Benatto, GADR, Lancia, AAS, Spataru, S, Poulsen, PB & Forchhammer, S 2022, 'Reconstruction and Calibration of Contactless Electroluminescence Images From Laser Line Scanning of Photovoltaic Modules', IEEE Journal of Photovoltaics, vol. PP, no. 99, 9736329. https://doi.org/10.1109/JPHOTOV.2022.3151327
2. Del Prado Santamaria, R, Dos Reis Benatto, GA, Lancia, AAS, Garaj, M, Thorsteinsson, S, Poulsen, PB & Spataru, SV 2021, Characterization of Electrical Parameters of Cracked Crystalline Silicon Solar Cells in Photovoltaic Modules. in Proceedings of 48th IEEE Photovoltaic Specialists Conference. IEEE, pp. 0846-0853, 48th IEEE Photovoltaic Specialists Conference, 20/06/2021. https://doi.org/10.1109/PVSC43889.2021.9519081
3. Benatto, GADR, Mantel, C, Santamaria Lancia, AA, Poulsen, PB, Forchhammer, S & Spataru, SV 2021, Laser Induced Luminescence Characterization of Mechanically Stressed PV Cells. in Proceedings of 48th IEEE Photovoltaic Specialists Conference. IEEE, pp. 1949-1953, 48th IEEE Photovoltaic Specialists Conference , 20/06/2021. https://doi.org/10.1109/PVSC43889.2021.9518751
4. Hass, TK, Spataru, S, Santamaria Lancia, AA, Parikh, H, Poulsen, PB & Benatto, GADR 2020, Computer Vision Method for Extracting an Induced Electroluminescence Signal from Photovoltaic Modules in Daylight Conditions Using Drone-Captured Images. in Proceedings of 37th European Photovoltaic Solar Energy Conference and Exhibition. pp. 1573-1579, 37th European Photovoltaic Solar Energy Conference and Exhibition, 07/09/2020. https://doi.org/10.4229/EUPVSEC20202020-5CV.3.44
5. Benatto, GADR, Santamaria Lancia, AA, Hass, TK, Poulsen, PB & Spataru, S 2020, Detection of Solar Cell Cracks by Laser Line Induced Lateral Currents and Luminescence Imaging. in Proceedings of 37th European Photovoltaic Solar Energy Conference and Exhibition. pp. 1053-1057, 37th European Photovoltaic Solar Energy Conference and Exhibition, 07/09/2020. https://doi.org/10.4229/EUPVSEC20202020-4AV.1.40
6. Benatto, GADR, Mantel, C, Spataru, SV, Santamaria Lancia, AA, Riedel, N, Thorsteinsson, S, Poulsen, P, Parikh, HR, Forchhammer, S & Séra, D 2020, 'Drone-Based Daylight Electroluminescence Imaging of PV Modules', IEEE Journal of Photovoltaics, vol. 10, no. 3, pp. 872 - 877. https://doi.org/10.1109/JPHOTOV.2020.2978068
7. Mantel, C, Villebro, F, Parikh, HR, Spataru, S, Benatto, GADR, Sera, D, Poulsen, PB & Forchhammer, S 2020, 'Method for Estimation and Correction of Perspective Distortion of Electroluminescence Images of Photovoltaic Panels', IEEE Journal of Photovoltaics, vol. 10, no. 6, pp. 1797-1802. https://doi.org/10.1109/JPHOTOV.2020.3019949
8. Spataru, S, Benatto, GADR, Hass, TK, Santamaria Lancia, AA, Poulsen, PB & Thorsteinsson, S 2020, Method for Evaluating the Severity of Solar Cell Cracks in Electroluminescence Images. in Proceedings of 37th European Photovoltaic Solar Energy Conference and Exhibition. pp. 1130-1135, 37th European Photovoltaic Solar Energy Conference and Exhibition, 07/09/2020. https://doi.org/10.4229/EUPVSEC20202020-4AV.2.31
9. Parikh, HR, Buratti, Y, Spataru, S, Villebro, F, Benatto, GADR, Poulsen, PB, Wendlandt, S, Kerekes, T, Sera, D & Hameiri, Z 2020, 'Solar Cell Cracks and Finger Failure Detection Using Statistical Parameters of Electroluminescence Images and Machine Learning', Applied Sciences, vol. 10, no. 24, 8834. https://doi.org/10.3390/app10248834

6. Utilisation of project results

The project has led to prototypes of both hardware and software which will be utilized commercially after a final maturing. UxV Technologies will produce the developed payload and Drone Systems will deliver the reporting platform to store and analyze the data. A patent application on the used technology in the project using lasers to drive luminescence for outdoor PV inspection was filed 20/10/2020 with the title “System for inspecting photovoltaic modules”. It was published online 2022-04-28 under application number WO2022084204A1.

Creative Sight has made a license agreement with DTU on exploiting the patent for drone applications and will therefore complete the value chain by buying the tool form UxV Technology and selling the hardware solution to end customers. In the project several end customers have been interviewed and therefore proof of market has been solidly identified.

The developed inspection tool is having similar value in the quality of outdoor luminescence inspection as a mobile laboratory which is the current state of the art. Here the mobile laboratory is brought to the site, and PV panels are dismantled for testing, or new panels are tested before installation. The cost of this service is orders of magnitude more costly than doing inspections from a drone with the DronEL tool, which is completely contactless, and the systems doesn’t have to touched at all.

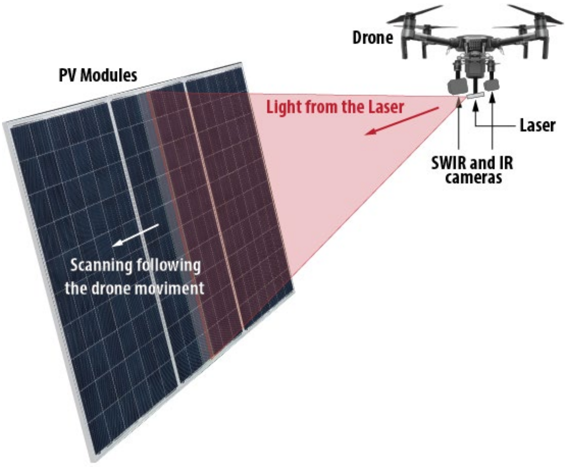


A few luminescence inspection companies are starting to enter the market, and most of them are doing inspections at night. Some companies offer this from a drone though for it to work the PV system have to be dismantled and a power supply (in some occasions powered by a battery) connected to the string to drive the luminescence. The time used for dismantling and connecting power to the solar panels is several orders of magnitude higher than for the DronEL solution where the onboard laser pumps the solar cells and drives the luminescence from them. The potential of the DronEL tool is therefore huge.

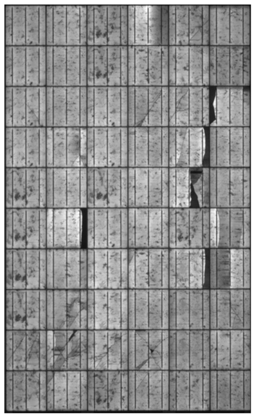
The DronEL tool is made so it fits standard commercial drones and can therefore easily be scaled. Most inspection companies already have a fleet of drones are swapping cameras for different inspections tasks. This solution fits this workflow, since the developed tool can then be mounted e.g. on an existing drone when a photovoltaic inspection task is needed to be done. Some customers might require an inspection by IR camera first and afterwards do EL inspection of certain parts of the solar farm. IR inspection are done from much bigger height and will usually be a full farm inspection and then afterwards the DronEL tool can be mounted for point of interest inspection defined by the IR inspection.

7. Project conclusion and perspective

The project aimed to further develop and commercialize a drone-based inspection solution that can make preventive troubleshooting on solar cells installed in the field. The project is based on an Innovation Fund Denmark supported Grand Solutions project (2017-2019), where a proof-of-concept of a drone solution that can take high-resolution luminescence images in flight in full sunlight was demonstrated as the first in the world. In this project, this leadership position was utilized to technically mature the developed concept further and bring this to commercialization.




Visual


Electroluminescence

The main activities of the project have been to realize a dedicated technical solution where all the technical units including on-board computer are assembled in a technical configuration in the style of the picture to the right. This unit will have both SWIR camera and line laser unit in it and is able to scan across the solar panels and automatically focus and adjust for optimum image quality. The laser line (800 nm) is pulsed, and the induced laser light is absorbed and part of it is re-emitted (1100 nm) where the camera is sensitive, and images are taken in lines and compiled via image processing. By taking multiple images with pulsating light from the laser, these can be subtracted, and sunlight filtered out, so the system works under all weather conditions that allow drone flying (both night and day). Furthermore, the photovoltaic system wiring need not to be disassembled as the injection of energy comes from the laser carried on the drone. The activities of the project had an iterative character, where hardware and software development took place in several maturation stages, and ended up with a technical solution that, based on artificial intelligence, can automatically identify and classify error types and generate a report. The solution also has third camera installed (RGB camera) for taking normal visual images and for easy navigation before starting the inspection. A reporting platform building on top of Drone Systems TeraPlan back-end have been realized where a solar installation can be virtually constructed from simple drone images and overlayed with the EL inspection images which can be analyzed and report generated automatically on potential actions to take.

Both hardware and software needs maturing after the project to successfully enter the market and meeting the demands here, which the commercial partners will ensure.