4. Cameras and photogrammetry

4.1. Sensors

Sensors that help gather data from the surrounding environment are primarily divided into passive and active sensors. Passive sensors measure (sun)light reflected from the objects or energy emitted by the object (E.g. heat or radiation). Cameras record electromagnetic radiation that the object reflects. Passive sensors include sensors connected to atmosphere and geo-physics that, for instance, measure atmospheric gas concentration or parameters of the magnetic field.

Active sensors send the electromagnetic radiation impulse from the UAV and then measure the characteristics of the pulse reflecting from the object. A good example would be a laser scanner that measures the time needed for the laser pulses to reach back and the intensity of reflection in comparison with the intensity of the initial pulse. When we know the air propagation speed of the signal, such practice helps determine the distance of the object from the sensor.

Often a UAV has multiple sensors. Laser scanner, for example, is installed together with a synchronized photo camera. In some cases, the UAV with sensors is just a part of a larger measuring system that has a permanent monitoring station on the ground and the UAV is used for occasional surveillance flights to get data that are more comprehensive. There are several sensors for monitoring the activities of the UAV as well (E.g. a barometer for determining the altitude). At the same time, such 'inner' data of the UAV is not yet fully used today, but the potential is there.

Apart from the technical data, what is also important in case of the sensors is their weight, size, power consumption and compatibility with the drone.

The two first parameters affect mainly flight dynamics, that is, indirectly, flight time and the ability to manoeuvre. Power consumption is, first and foremost, dependent on whether the sensor has an autonomous battery or it uses the energy provided by the battery of the drone. In the former case, the pilot needs to take into consideration charging an additional set of batteries and calculating their capacity, what is more, the total weight of the UAV increases. In the latter case, the total weight of the UAV is smaller, but only a part of the total capacity of the battery is left for performing the flight, a capacity that the flight planning software is unable to calculate correctly. Compatibility with the drone can happen on different levels: only sharing the energy, uni- or bilateral teleoperation (ühe- või kahepoolne drooni sidekanali kasutamine) and operating the sensor by it; changing the flight trajectory of the drone with the help of real-time sensor based data processing, etc.

- The most simple case is when the UAV and the sensor are just physically connected and there is no 'communication' between them: the UAV carries the sensor around.
- In case of unilateral teleoperation between the sensor and the UAV, the pilot is able to choose the 'picture' and telemetrics, but is unable to control the sensor in any way;
- In case of a bilateral teleoperation, the pilot is able to view the 'picture' transmitted by the sensor and the telemetrics, and, if needed, change the parameters of the sensors during the flight using communication channels between the UAV and the controller on the ground. The pilot can direct the cameras to the point of interest (POI), change the zoom, take pictures/videos at any time, turn off the sensor to save power, etc.
- Incorporating the highest level sensors and UAVs, the sensor becomes an integral part of the UAV, in which case the data is usually analysed in real time by machine learning algorithms, and thus also the flight can be changed according to the results of data analysis. Functions such as tracking or follow me serve as a good example of the drone constantly identifying the object by camera, monitoring it and changing the flight in a way that it remains at a certain distance from the object, at the same time avoiding collisions with other objects.

An important interface between the drone and its many sensors, cameras in particular, is a gimbal i.e. camera stabilizer that considerably reduces the vibration caused by the drone (see image 10). This way the camera keeps the same angle regardless of the movement of the UAV. Using a decent gimbal is the precondition of a more precise planning of data collection, since it enables to calculate the terrestrial projection of images and measurements, necessary overlay and, as a result, accomplish the ground sampling distance (GSD). In case we do not use gimbal, for the flight to be even, we need to prolong flight trajectories significantly as well as distance between runways etc., otherwise the vibration might affect the data and leave areas uncovered. All the above steps help to reduce the area covered by the data while retaining the same data volume.

Gimbal is especially important in case of multirotors, since it smooths the tilt of the drone. By nature, drone planes are significantly more stable and therefore need gimbal only with cameras that have longer focal length. In order to function immaculately, gimbals require accurate balancing and calibration depending on temperature, a procedure that always needs to be repeated upon the change of the sensor. Therefore, the majority of camera drones are already designed with an integrated gimbal. Such a solution makes gimbal cameras easily exchangeable, but only by versions offered by one and the same manufacturer or rather only within one drone series. A huge drawback is that no standard connections or mounts across manufacturers have been agreed upon (yet). Thus, buying a new UAV often means that all gimbal cameras and UAV batteries have to be replaced as well. It is, however, possible to buy a so-called empty gimbal that can be adjusted by the user to fit a specific sensor. Gremsy is the leading manufacturer of camera gimbal stabilizers for drones.

Image 1. Left to right: Gremsy Mio gimbal, Yuneec E90 gimbal camera and DJI H20N gimbal camera with multiple sensors and a laser rangefinder.

A 2-axis gimbal camera that stabilizes the sensor over two axis should be enough for mapping. For search and/or pursuit, a 3-axis gimbal is needed in order to be able to rotate the sensor around its vertical axis. In this case, the sensor ideally needs 360° of free space for rotation, and multirotor drones need extra support legs that can be pulled up during the flight.

Regular cameras, or RGB cameras or their modified versions are the most widely used types of cameras. Next up are multi- and hyperspectral cameras, thermal cameras and laser scanners (colloquially *LiDARs*). An excellent overview of the most common sensors (excl. thermal cameras) can be found in Nex *et al.,* (2022).

In addition, many different sensors can be integrated or attached to the UAVs: sonars, radars, magnetometers, water samplers, insect traps, etc. The latter are quite uncommon or even single innovative applications.

Before the detailed introduction of the sensors, please be reminded of the electromagnetic spectre (Image 11).

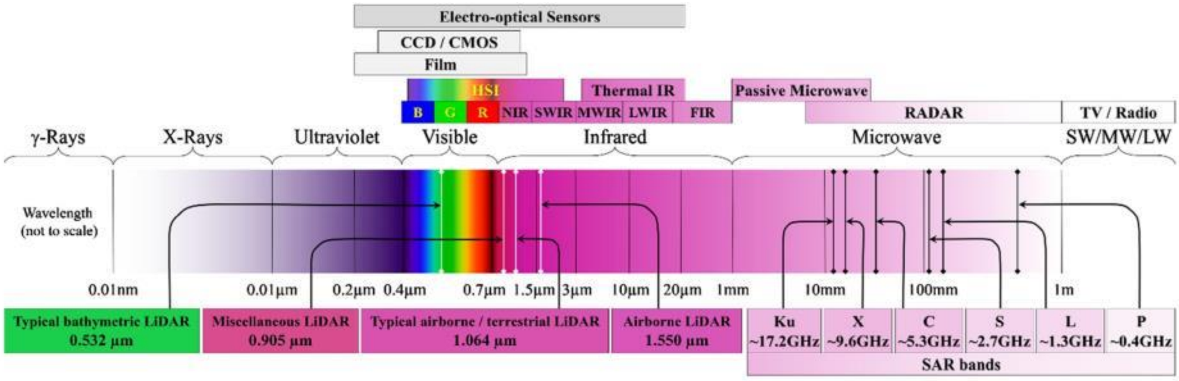
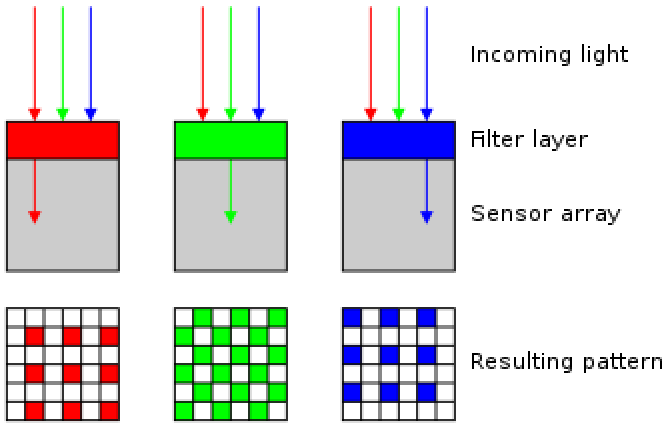


Image 2. Electromagnetic spectre and remote sensing methods connected to it (Toth and Jóźków, 2016).

4.2. RGB or photo cameras

Regular cameras capture three ‘colours’ from the visual light spectrum i.e. narrow spectrum: red (R), green (G), and blue (B) (Image 7). The separation of colours is done using filters that cover specific sensor elements i.e. pixels, forming a Bayer filter.



Joonis 3. Bayeri filter fotokaamera sensori ees.

An attentive reader will notice that in comparison with the red pixels, there are twice as many green ones (Image 7). This is due to the fact that a human eye is most perceptive of different shades of green. An image with different colours is created by interpolating and adding information from adjacent colours to each pixel. This process can occur inside the camera, in which case final information is recorded either in a .jpeg- or .tiff- file, or later in the computer, in which case the image is saved in the camera in a raw pixel format (.dgn, .arw, .raw, etc.). Raw file stores all the information recorded by the sensor and presents therefore best possibilities for later processing. However, the files are extremely large and most image processing software has no means to deal with it. In addition to such ‘mixing’ of colours, the camera also (based on manufacturer and settings) improves images: removes distortions, changes colour balance and saturation, adjusts brightness, etc. Recent years have seen exceedingly more adjustments implemented by AI that change the image by small areas: photos of grandma with no wrinkles, etc. It is wise to disable such automatic adjustments when drone images are used for research and surveillance.

Martínez-Fernández *et al.* (2022) have conducted an interesting study concerning the effects of using different picture formats in photogrammetry. Generally, no significant impact on generating 3D models or orthophotos was detected, except in the cases when using .jpg format automatic distortion correction was disabled in camera. Therefore, if possible, this function should be turned off in camera. In addition, my personal experience has led me to use mostly .jpeg format, since the changes are minimal there. It is only in case of challenging lighting conditions (bright sun, low light, sharp contrasts) when the use of raw format in images is advisable. When planning a flight it must be considered that saving larger raw images on the memory card takes longer and therefore the UAV needs to fly slower.

The most important parameters of the UAV camera are as follows:

- Physical size of the camera sensor
- Number of pixels of the camera sensor
- Dynamic range of the camera sensor and image colour depth
- Image recording speed of the camera

A rule that applies to all these parameters is that the bigger the better. The parameters of physical size and dynamic range of UAV cameras are usually quite poor, and camera lenses can be changed only in few models. Lenses also tend to be of lower quality and the number and range of changeable parameters is small. What is more, less expensive UAV cameras have an electronic rolling shutter, in which case the data is derived from the camera sensor line by line. This means that the images come is a slightly distorted manner, since the drone is on the move during the data reading process. Some photogrammetry software (E.g. Metashape, Pix4D) can compensate this negative effect on precision, but not all. Read more on the issue in Vautherin *et al.* (2016).

It is quite popular to use a regular compact camera (E.g. Sony Alpha series) to capture the surrounding with a UAV, since these allow shorter recording time, a wide range of lenses and better image quality. A drawback of compact cameras is user comfort, because they are not by default connected to the UAV in any way. Such cameras, at least in the case of multirotors, need a gimbal calibrated for the camera and its lens. Flight controller also needs to be adjusted to the camera to enable taking pictures using the UAV communication channels or flight plan. Nevertheless, integration between the UAV and camera is, at the onset, not such a great problem for contemporary cameras and flight controllers and a few inexpensive cables and/or adapters would suffice.

In addition to the previous, the relatively large weight of the compact camera in comparison to the specific UAV cameras makes its use uncomfortable. The larger weight is reflected, first and foremost, in the longer flight time of the drone. As a rule, wide-angle lenses are used for mapping, and the capture command comes from the flight controller according to the pre-planned flight plan. As for lenses, their weight is also the main constraint and therefore the lightest and smallest, the so-called *pancake* lenses are preferred. With the increasing selection and quality, gimbal cameras that can be integrated and exchanged have become more and more popular. Thus, most of the largest UAV manufacturers (E.g. DJI and Yuneec) offer a considerable choice of cameras (incl. multispectral- and thermal cameras) for their platforms meant for professionals (E.g. DJI Matrice (see also image Image 4) or Yuneec H520). DJI even has a camera optimized especially for photogrammetry Zenmuse P1 that exhibits excellent image quality.

Image 4. Integrated gimbal cameras meant for DJI Matrice series, photographs from the manufacturer's web page.

Cameras constructed specifically for UAV aero mapping (E.g. Phase One P3) offer the best image quality, but come inevitably with a high price. A new trend on offer are the synchronized multi-camera systems in which case cameras simultaneously take pictures from different angles (E.g. Rainpoo D64P). Such a solution is efficient in 3D mapping of urban environment, since during one flight it produces multiple images from different angles at once. With the help of software, a DJI M300 along with P1 camera will fulfil the same task by flying slower and taking pictures from different angles by turning the gimbal (*smart oblique* function).

Cameras equipped with contemporary photogrammetry provide a relatively inexpensive opportunity for the pilot to get a 3D point cloud, digital surface model as well as an orthophoto of the object of interest. The latter is usually categorized (E.g. differentiate types of vegetation) using first and foremost spectral information provided by the camera on the three intervals of the spectrum i.e. bands. However, significant shortcomings appear when spectral information is used by regular digital cameras (Logie and Coburn, 2018):

- The three recorded spectral bands are very wide (usually 70-100 nm) and have a partial overlap;
- Spectral and radiometric response functions of cameras are uncalibrated and different cameras show spectral ambiguity between the bands;
- Digital number (DN) of the sensor's pixels is in a non-linear relationship with light intensity and the user does not know that without calibration;
- In case of using JPEG images significant information processing and distortion occurs inside camera, the precise nature of which is unknown to the user (Cramer *et al*, 2017).

Some of the above impediments can be overcome by calibrating the camera and its lens, but this requires special tools and knowledge and is thus a relatively expensive practice. What is more, because of these deficiencies it is quite labour-intensive for regular digital cameras to use spectral information and potentially large errors occur, for example, in case of changing light conditions. Therefore, an orthophoto taken with a camera is suitable only for rough classification where the spectral signature of objects also has to be clearly distinguished. In order to get more precise and controlled spectral information a calibrated multi- or hyperspectral camera needs to be used.

4.3. Multispectral cameras

In comparison with regular cameras, multispectral cameras have the capacity to record a dozen of non-overlapping spectral intervals or bands with the width 10–40 nm.

Such cameras are mainly used for the study of vegetation, in which case in addition to the visible (VIS) also near-infrared (NIR) part of the spectre is measured, since this interval is sensitive to chlorophyll.

Hyperspectral cameras can capture hundreds of channels, which usually range between 3–10 nm. One camera can usually cover a VIS-NIR interval (400–1000 nm) or Short-Wave InfraRed (SWIR) spectral band with a wavelength of 1000–2500 nm. VIS-NIR interval is more suited for the study of vegetation and SWIR is more used for geological/mineralogical mapping (Image 11). Most of the available cameras are optimized for covering either one or the other interval.

Comprehensive overview articles on both multi- as well as hyperspectral cameras can be found in Aasen et al. (2018) and Nex et al. (2022).

Multispectral cameras have a modular design meaning that separate camera modules, each covered by a filter passing through one spectrum interval only, simultaneously photograph each wavelength. For example, AgEagle Micasense RedEdge consists of six separate cameras: five of them photograph in their specific spectral bands and one is a regular RGB camera. Some multispectral cameras can be assembled in a way that the user can choose the number of modules as well as filters placed in front of the lens (E.g. Maia M2 or Mapir Kernel2 cameras). Some camera systems (E.g. AgEagle Micasense Altum-PT or Sentera 6XT) incorporate in addition to the multispectral- and photo camera also a thermal camera (Image 14).

It is important to remember that different cameras most likely have also different filters although manufacturers may call the corresponding channel with the same name. Therefore, spectral signatures captured by different cameras are not comparable per se; in addition to the above differences, also differences stemming from calibration come into play.

Multispectral cameras whose task is to connect the collected data with satellite data are also available for purchase. The recording spectral channels of such cameras are (almost) identical to the with the channel's observable from the satellites – satellite Sentinel 2, for example, is 'compatible' with multispectral camera Maia S2, and satellite WorldView-2 with Maia WV camera.

The described cameras are integrated with the UAV mainly through power supply and shutter release. In addition, some models allow the use of the UAV's precision GNSS for georeferencing the images. Image preview can be generally configured and viewed on multispectral camera by the camera's own Wifi or Bluetooth connection. Larger UAV manufacturers offer drones with more fully integrated spectral cameras (E.g. DJI Mavic 3M or Delair UX11 AG), that, through the controller, enable real time monitoring of the information collected by the sensor(s) and even results calculated on the basis of it such as the map of Normalized Difference Vegetation Index (NDVI).

The number of pixels of the sensors of multispectral cameras is considerably smaller than in photo cameras. The regular number of pixels starts from 1,2 Mpx (E.g. Micasense RedEdge, Maia), but the newest models have sensors with a resolution up to 5 Mpx (E.g. DJI Mavic 3 M). This means that ground sampling distance (GSD) is shorter between pixels, and in order to see the objects at the same level of detail as with a RGB camera, you must fly on a lower altitude. In case of the systems where the UAV also has an additional RGB camera, the manufacturers tend to advertise first and foremost only the resolution of the photo camera. The resolution of the spectral camera module with its more modest distance sampling ability is usually not highlighted in the manuals. The lenses of multispectral cameras are in general not replaceable, yet filters in front of camera modules can be replaced in some cameras.

In order to acquire spectral reference from the digital number (DN) initially recorded by the sensor, multi-stage calibration is used. A more ambitious user of spectral information might want to read overviews by Aaseni et al. (2018). What is more, Cao et al. (2020) provides an excellent example of the calibration of data of the UAV's multispectral camera (Image 13).

Fig. 1. Simplified flow of information from surface radiance to reflectance maps using multispectral drone sensors. Surface radiance is measured as at-sensor radiance for each band by the drone sensor and saved as digital numbers (DNs) in an image file. Image DNs are then converted ("calibrated") into reflectance values using an image of a reflectance standard acquired at the time point of the survey. The resulting reflectance maps for each of the sensor's bands can then be used to calculate VIs or as direct inputs for classification. Drone symbol by Mike Rowe from the Noun Project (CC-BY, http://thenounproject.com).

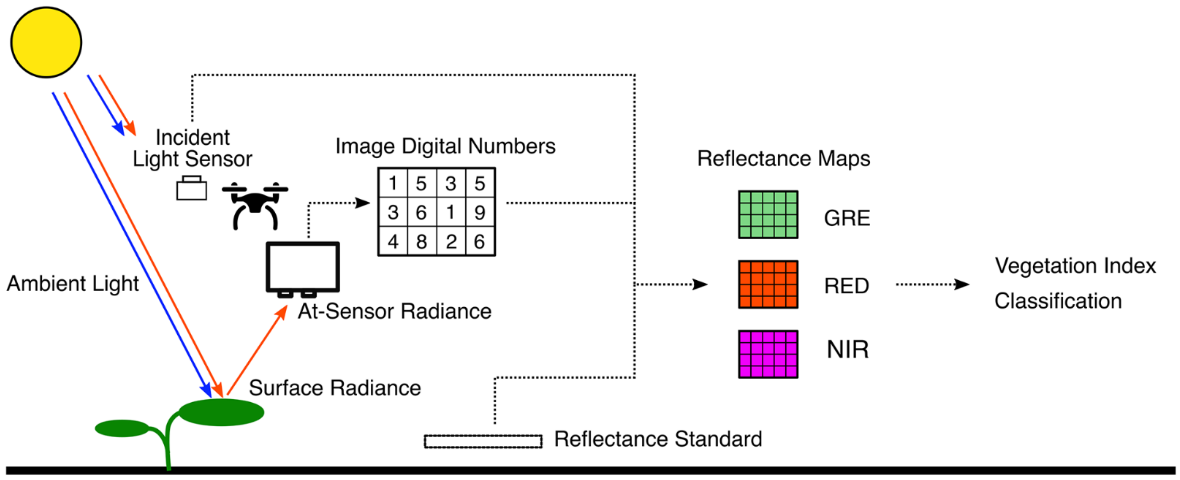


Image 5. A simplified workflow of the information collected by the drone's multispectral camera according to Assmann *et al.* (2019).

The majority of camera and lens calibration is already done inside the camera, but to get final spectral reflectance values reference panels are usually used. Quite accurate reflectance values have been recorded in laboratory conditions, and pictures taken of them immediately before and after are used to calibrate pictures taken during the flight. As in many occasions, these couple of images from the reference panel are the sole basis for calibration the manufacturers' instructions have to be followed extra carefully. In addition, reference panel values will change in time as well – these should be re-measured in lab conditions after every couple of years.

Such approach to calibration presupposes that solar radiation will remain the same during flight or it changes in a linear way – in reality, this supposition is never quite fulfilled. Data from radiation sensor (Incident Light Sensor (ILS)) is used to monitor the changing light conditions during the flight. Most of the multispectral camera providers offer ILS as an extra accessory. Assmann *et al.* (2019) offers good advice on working with multispectral cameras in conditions matching to Estonia. Camera's internal temperature has its effect on the results – prior to actual data collection, the camera must work for at least 15 minutes in order to maintain a stable internal temperature as explained by Olsson *et al.* (2021).

A fast-growing field of multispectral cameras is precision farming, with the help of which plant stress or the spread of pests accompanied by lack of nutrition or water can be monitored by portions of fields even before the death of the plants. See more about the use of UAVs in precision farming in Rejeb *et al.* (2022).

To conclude with, some remarks on **hyperspectral cameras**. These devices give the most abundant and precise spectral information, but are very expensive, and the data acquired by them needs specific and device-based processing. Hyperspectral cameras use several different ways to read the information from the sensors. Differently from the RGB and multispectral cameras, hyperspectral cameras do not yet enable reading the data from all the pixels simultaneously. Data reading systems are quite different (E.g. see Aasen *et al*, 2018), but all of them make the volume of data to be processed very large and thus, up until now, the use of hyperspectral cameras has remained restricted to the field of scientific research.

Overviews on different technologies used in hyperspectral cameras can be found in Adão *et al.* (2017) and in slightly newer article by Nex *et al.* (2022).

Image 6. Examples of multi- and hyperspectral cameras mentioned in the chapter, photographs from the manufacturer's web pages.

4.4. Thermal cameras

Thermal cameras allow us to see temperature differences of objects. For that, they have sensors sensitive to 7–14 µm wavelengths. In case of thermal radiation, heat is emitted or radiated and not reflected. Because of this, as opposed to regular photo cameras, no external radiation source is needed for the functioning of thermal cameras, but each object with a temperature above absolute zero emits heat by itself. On the one hand, it allows seeing objects in what is an absolute darkness for human eyes; on the other hand, however, it creates much noise, since the camera itself is a source of observable radiation.

Thermal cameras most commonly used on UAVs, microbolometers, do not have thermal control and are therefore sensitive to both external- and camera internal temperature fluctuations. Military sector uses actively cooled thermal imaging cameras that are more stable, create less noise and are more sensitive to temperature fluctuations. All these advantages result in a higher price range, the cameras are larger and heavier and need more energy.

One single pixel of a heat sensitive sensor is considerably larger than in RGB cameras and they cannot stand immediately adjacent to each other without significant interference like in RGB sensors. Therefore, sensors in thermal imaging cameras have a low resolution – the resolution of the best cameras for UAVs in civilian use is generally 640x512 pixels (E.g. Workswell WIRIS 640 and FLIR Vue Pro). Sometimes in-camera merging of frames is used in order to get, for example, thermal images with HD (1920x1080) resolution (E.g FLIR Ultramax and Wiris Superresolution technologies).

You can buy radiometrically calibrated (E.g. FLIR VUE PRO R) and uncalibrated (E.g. FLIR VUE PRO) thermal cameras. Calibration takes place in factory labs in relation to reference sources with set temperature, and after this procedure, the measurements of a particular pixel can be converted into absolute temperature. Therefore, radiometrically calibrated thermal cameras are twice as expensive in comparison with uncalibrated cameras. In the output recorded by calibrated cameras, usually in rjpeg format, each pixel has its own temperature value aligned by calibration, and in addition to that, during post-processing with special software, the image can be converted pixel by pixel to absolute temperature. Uncalibrated cameras only show relative temperature differences within one frame, thus, absolute temperatures are less precise and consistent.

At the same time the, in comparison to the sensitivity of the sensor, the accuracy of calibrated thermal cameras is also considerably lower. For instance, the absolute accuracy of the more expensive UAV thermal cameras is ±2 % i.e. ±2 °C (E.g. WIRIS Enterprise), whereas the camera can distinguish 0.03-degree temperature differences. The accuracy of cheaper cameras is usually ±5 % or ±5 °C. An example from everyday – it is difficult to detect a single person's fever with thermal camera, since it is defined by a 2–3-degree difference from 'normal' on absolute temperature scale – the difference, thus, remains within the measurement error. At the same time, it is very easy to spot a person with a fever, if on the thermal image he stands side by side with a person with 'normal' body temperature.

Readings of pixels of uncooled sensors of thermal cameras start 'drifting' very quickly, sometimes in minutes thanks to susceptibility to outer conditions, and in addition, the pixels themselves have different sensitivity. To stabilize the gain and offset for pixels the so-called *non-uniformity correction* method (NUC) is used (sometimes referred to as *flat field correction* (FFC)). For that, all the pixels are heated equally for a brief moment and differences in the change in readings are already used to calibrate pixels in relation to each other. During the non-uniformity correction (usually a couple of seconds), the camera is unable to capture a thermal image. Frame density depends on the camera, instructions of the manufacturer and variability of the external environment.

As NUC calibration occurs inside the camera, it does not reduce image distortions caused by optics (E.g. vignetting), etc. External calibrators for thermal cameras are available (E.g. Teax Calibrator) that are located in front of the lens and help (partially) reduce optical distortions. The effects of external- and internal temperatures, wind and optics on the readings of thermal cameras as well as calibrating them out, are described in Aragon *et al.* (2020) (also the source for Image 15), and Kelly *et al.* (2019).

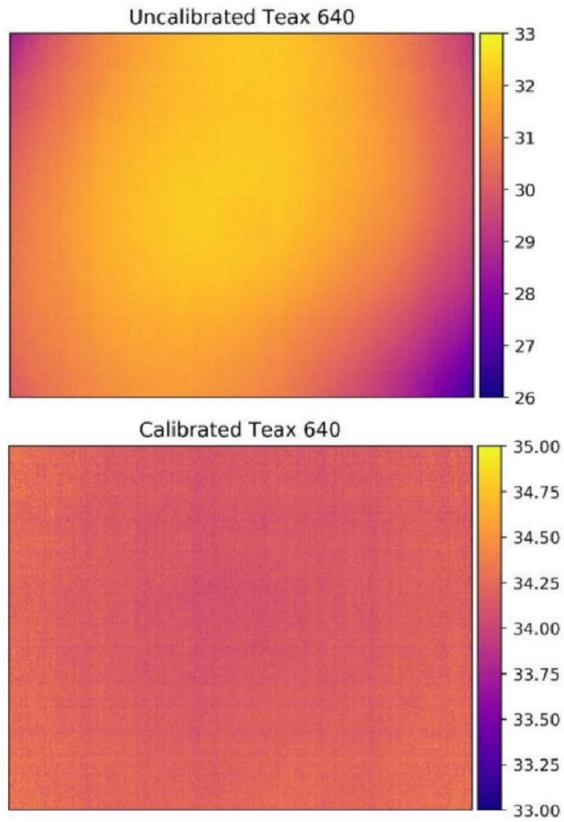


Image 7. Uncalibrated and calibrated thermal image. The temperature of the test object was 34.44 °C.

One of the practical problems of thermal cameras is that because of low spatial resolution, it is difficult, based only on a thermal image to determine the object that causes thermal anomalies. Moreover, several objects within close proximity, i.e. herds, cannot be distinguished with the precision of an individual by a thermal image. Thus, camera systems that combine thermal- and photo cameras have become increasingly common – thermal camera will help to locate the object and photo camera identify its characteristics (E.g. FLIR DUO or Teax ThermalCapture). Some UAV manufacturers sell configurable gimbal cameras for professional use meant for conducting thermographic surveys (E.g. gimbal cameras DJI H20T, Yuneec E10T). In addition to magnifying and wide-angle camera, such solutions also have an integrated laser range finder that allows the UAV to specify the coordinates of an object on the ground or water in real time. Such solutions are used for search and rescue purposes mainly.

There are also compact, foldable drones (E.g. DJI Mavic 3T and Autel Dual EVO II), the camera of which combines completely integrated thermal- and photo camera, and which are quite equal in quality to the more expensive analogues.

Thermal and optical camera systems (*EO/IR*) produced for military sector, and search and rescue purposes use high extent of machine learning in their software in order for the UAV to be able to identify and track the objects of interest. Typically, such UAVs have high power zoom lenses (E.g. Threod ORCA, sensor system integrated with gimbal) (Image 12).

 FLIR Vue PRO	Autel Dual EVO II 

Image 8. Some images of thermal cameras mentioned in the chapter.

A short description of photogrammetry

Photogrammetry of UAV collected data is one of the most common data processing methods that can correct geometric distortions on single photos, create 3D models of objects and mosaic together orthophotos. Successful use of photogrammetry requires specific arrangement of photos and considering several circumstances.

In comparison with traditional precisely calibrated metric aero photo cameras, the involvement of UAVs and uncalibrated cameras causes instability in the camera platform, resulting in lower quality aero photos (Hardin and Jensen, 2011). Turner *et al*. (2014) indicates at the challenges of using UAV-based photogrammetry: considerable scale variation, high overlaps, images with very different orientation and large location shifts resulting from low flight altitude and relief. Since the list of possible problems is long, methods of traditional photogrammetry are no longer suitable for such image processing and a different approach is needed.

Snavely (2008) has provided a description of the novel approach. UAV photogrammetry here means *Structure from Motion – Multi View Stereo* workflow (SfM-MVS, hereinafter SfM). We are dealing with a method using the principles of traditional photogrammetry that combines traditional workflow with computer vision and mathematical optimization. This is the innovation by Snavely (2008), who was the first to integrate the aforementioned development into one single process. As a result of SfM workflow based on images, a 3D-point cloud is created and geometric distortion parameters of the camera, location and orientation are calculated on an ongoing basis. As a logical sequel, a surface model is created from a 3D-point cloud, and with the help of its single photos, an orthophoto is 'fused' together.

Ground reference points can be added to SfM workflow; these help to tie the created 3D model, at first relative and without any scale, to the real object scale and spatial location.

Summed up the main stages of SfM photogrammetry are as follows:

1. Unique key points are looked for from the photos using colour gradients i.e. changes in different scales. Different machine vision algorithms (E.g. SIFT-algorithm) are used for the search;
2. Photos will be matched using different key points. Matching key points are connected and thus, tie points are formed;
3. A mathematical model of the camera is calculated based on the tie points of the matched photos, with the help of which geometric distortions of images are corrected and a relative 3D model of the entire object and the layout of shooting locations is compiled. All this takes

place during a large-scale bundle adjustment process. As a result, a mathematical model of the camera, relative shooting locations and a sparse point cloud of the object are produced.

4. The above is used as an input to create a dense point cloud with MVS algorithms;
5. A dense point cloud is used for the calculation of a simplified, uninterrupted 3D mesh or a Digital Surface Model (DSM). These data already allow to mosaic an ortho photo from single photos;
6. A dense point cloud can be classified by separating, for example, terrestrial points from the points of buildings and vegetation. Only points belonging to the class of terrestrial points allow for the calculation of a Digital Elevation Model (DEM) (also Digital Terrain Model (DTM)). In the case of vegetation, DSM – DEM will give a Canopy Height Model (CHM) that would characterise the height of the vegetation. Today most of the more common SfM programmes possess the capability of classifying point clouds. Generally relatively simple geometry-based thresholds are used for the classification of point clouds; however, the importance of machine learning methods is on the increase;

On the processes and problems connected to SfM photogrammetry, see Harwin & Lucieer (2012), also the source of the following Image 18.

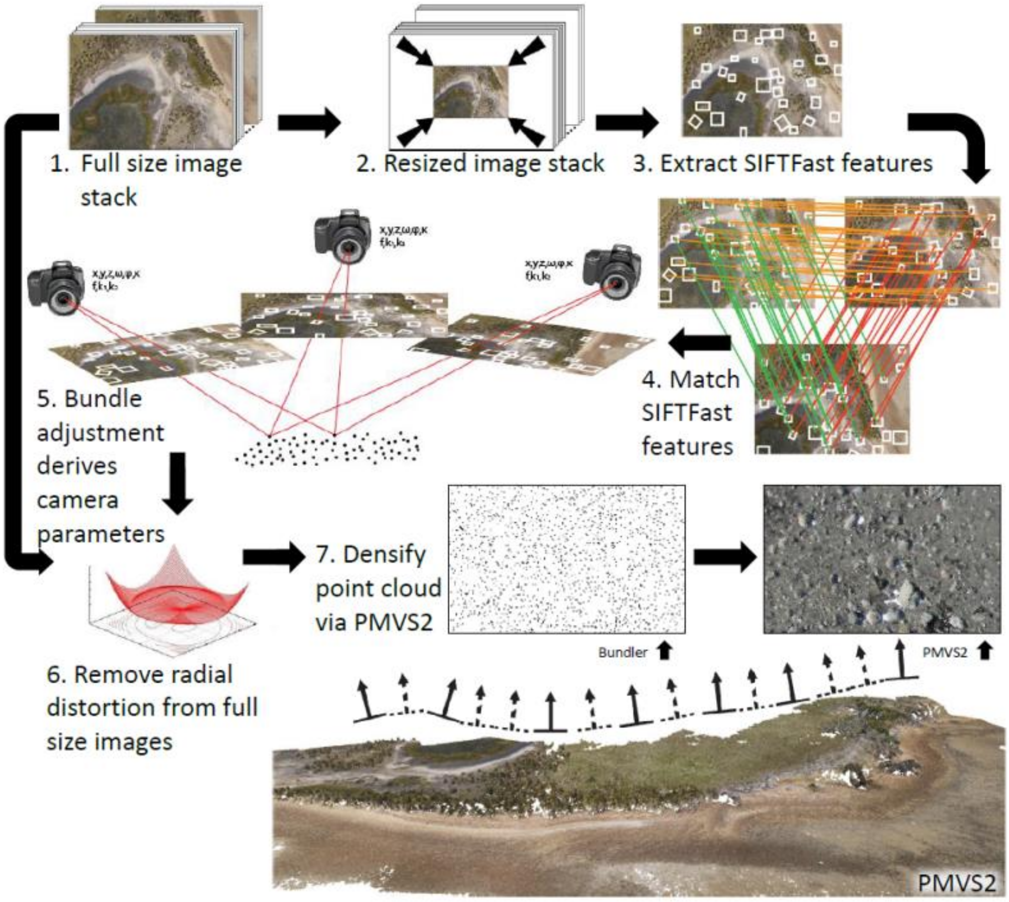


Image 24. Main stages of SfM photogrammetry (Harwin & Lucieer, 2012).

The use of SfM method generally presupposes the following:

1) Objects to be photographed have a sufficiently unique texture, since SfM method does not function in the case of water, strongly reflective objects or uniformly coloured or patterned objects.

2) The object does (almost) not change during the shooting (E.g. a typical problem is the branches in the wind and moving cars, but also reflective objects change on the images, since shooting from different angles, the object shows new reflection. The SfM method is more tolerant as to the light, scale and change of orientation, but considerable changes in these parameters also render the method imprecise.
3) A large overlay of photos is necessary – typically ca 70% both diagonally and length wise, with more complicated objects even up to 90%. Each point we want to show later in the model needs to be photographed minimally from at least 3–5 different locations, and each point has to be surrounded by at least a minimum change of colour recognizable by the SfM. Forest, for example, is a difficult object for SfM method, since we are dealing with a similar and repetitive pattern, and, in addition, there are many narrow spaces between the trees that cannot be photographed from different angles. In case of such difficult objects, we need an increased number of overlays and more photos from different angles. Flying higher, enables one image to cover a larger area, making it more probable to find unique key points; in addition, this way we can shoot with greater radiometric resolution and capture minute differences much better. Generally, the SfM does not 'penetrate' the even slightly denser forests. Taking photos from different angles helps to improve the mathematical camera model significantly, and therefore it is useful to add some angle images to the end of a regular 'straight-down' mapping flight (James *et al.*, 2019).

NB! We hereby need to stress the difference between data produced by a SfM point cloud and data produced by laser scanners, since the point cloud produced by scanners does generally penetrate the flora and will thus give information on the internal structure of the vegetation as well as the ground beneath it (Image 25).

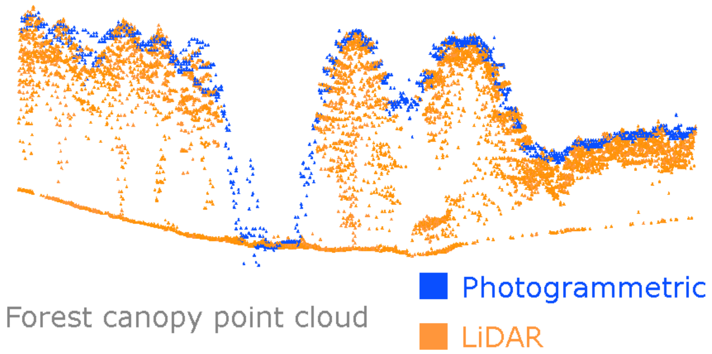


Image 9. Comparison of photogrammetry and LIDAR point clouds (Lisein *et al*., 2013).

The point cloud of UAV photogrammetry thus rather reflects the 'top layer' of the photographed objects.

The most well-known programmes employing SfM method include Agisoft MetaShape and Pix4D. The latter comes along with a special flight planner Pix4Dcapture. DJI, the largest UAV manufacturer, also has its own SfM software (DJI Terra). Several freeware programmes have been developed as well, the best known are MicMac and WebODM. Contemporary commercial software is quite highly automatized and the users might even not come into contact with a large part of its nuances. However, an informed user has the opportunity to check the results in detail and change different settings if necessary. With the help of Internet search tools you can easily find different workflows and descriptions of practices how to get the best results using the software. A quite recent overview of SfM software and workflow along with the use of UAVs can be found in Pepe *et al.*, (2022).

In addition to the regular, so called PC installed software, several cloud services are available for the informed users. There the user can upload his photos and after a short while, an ortho photo and 3D model is sent back. However, in this case it is significantly more difficult for the user to control the workflow or accuracy. A most well known spot offering such service is DroneDeploy.

In case of photogrammetry workflow, we need to take into consideration large calculation volumes that require a computer capable of processing larger masses of data. In several software, the calculation stages have been optimised for the use of graphical processor units (GPU) – a good video card is a vital part of SfM workstation.

Some software enable partial cloud calculation, in which case the calculation of the most voluminous stages can be commissioned from the net, at the same time maintaining a total control over the parameters. The SfM method brings along voluminous calculation as well as information noise, therefore, all software uses internal optimisation and intermediate filtration. Likewise, the algorithms and their methods of application are different. All of these circumstances are reflected in the results – with different programmes we get different results using the same input. Therefore, if possible, similar hard- and software and processing parameters must be used in recurring surveys requiring great precision. Most software compiles an automatic summary of the entire workflow, listing also all the parameters. This summary needs to be saved as metadata alongside SfM results.

In conclusion, SfM photogrammetry is currently the cheapest method for the creation of 3D models and ortho photos of an object, whereas also multispectral or thermal images can be the data source for SfM photogrammetry input. If we were to criticise, then we are dealing with a demanding method that requires taking into consideration many different factors. This is supported by the following table (Table 1) presenting a detailed summary by Iglhaut *et al.*, (2019).

Table 1. Parameters influencing the results of SfM photogrammetry (Iglhaut *et al*., 2019).

Domain	**Variable**	**Recommendation**
Scene	Texture	High surface contrast to allow for feature-point detection
	Pattern repetition	Increase overlap and increase accuracy of geotags
	Moving features	Avoid!
	Occlusions	Increase overlap and viewing angles!
Lighting conditions	Sun angle	High! Solar noon is ideal!
	Weather	Overcast provides even lighting (ambient occlusion) for structural (RGB) surveys. For spectral surveys little atmospheric influence may be required, clear skies.
	Changing illumination	Avoid!
Camera parameters	Focal length	Wide but not too wide to minimize distortions. 28–35 mm is a good basis (James et al. 2012)
	Exposure	Well exposed
	- Aperture	Small for max DOF*, f/8 an advisable default
	- Shutter speed	High for reduced motion blur*, ground speed (m/s) * exposure time (s) = blurred pixel
	- ISO	Low for min noise*, auto-ISO an advisable default *Ideal scenario, but will always be a compromise between these three parameters
	Pixel pitch	As high as is practical. Physical pixel size positively influences dynamic range and sensitivity

Survey characteristics	Overlap View angles Survey range	High, > 70% forward and lateral, for forests min 80%, thermal images 90% Add oblique photos for the better calculation of camera and 3D model! For the production of ortho photos use only vertical images! With increasing distance to the object/scene (decreasing GSD) survey precision degrades.
Processing parameters	SfM—matching - Image scale - Key points MVS – densification Secondary products	Downscaling the image considerably decreases the volume of calculation, but it also decreases the number of key points On different scales the matchability of images can be of various efficiency Images may be also scaled down in case of a dense point cloud, decreasing thus the volume of calculations as well as the final number of key points found Multitude of algorithms exist for converting point clouds into surfaces and the results will depend on specific method

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