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REVIEW ARTICLE

A review on advancing agricultural practices using photogrammetric images

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Abstract

Photogrammetry is a technique that involves the extraction of geometric information from two-dimensional images (2D). It is widely utilized in various fields for the creation of digital elevation models (DEM), orthomosaics and three-dimensional (3D) reconstructions of landscapes. In agriculture it is applied to obtain accurate and detailed spatial data for field variability mapping. It serves as a powerful tool in modern agriculture, contributing to high throughput phenotyping, monitoring growth patterns, pest attacks and nutrient deficiencies further helping in efficient resource management and decision-making about important farming operations. Real time monitoring further enhances its applicability in agriculture through the integration of photogrammetry with other technologies like drones, artificial intelligence and remote sensing. By harnessing the power of photogrammetry, stakeholders in the agricultural sector can unlock new possibilities for precision agriculture, resource optimization and ecosystem stewardship. Totally 300 articles were collected related to the topic of review from various sources in that nearly 100 articles were used to explore about photogrammetry progression, principles and software for processing images and mainly underscores the applications that offer farmers to enhance productivity by reducing environmental impact. The potential challenges and future directions in photogrammetric applications in agriculture are also discussed, highlighting the need for continued research and innovation to address evolving agricultural demands and sustainability goals

Keywords: 3D modelling; orthomosaic; point cloud; sensors; stereoview

Introduction

A technology designed to facilitate the development of maps, photogrammetry is a straightforward documentation technique that uses photographs for surveying and mapmaking. It is capable of extracting exact 3D measurements and comprehensive object data from many images (1, 2). In 1851, French inventor Aime Laussedat had an idea for a mapping camera but failed to bring it to fruition. The invention of photography in the middle of the nineteenth century was followed fifty years later by the emergence of photogrammetry. French surveyor Dominique F. Arago proposed creating a topographic map using pictures in 1840. Albrecht Meydenbauer, a Prussian architect, used the word "photogrammetry" in his 1867 publication "Die Photometrographie." The development of repetitive trigonometric software, made possible by the introduction of computers in the 1980s, allowed for the triangulation of three-dimensional points, especially in digital photography (1).

In its broadest sense, photography is the process of turning the real 3D environment into 2D pictures. The mechanism causing this 3D to 2D conversion is the camera. Nonetheless, the 3D environment cannot be fully projected onto 2D, which means some information most notably depth is lost. On the other hand, photogrammetry reverses this process by projecting or translating 2D pictures back into the real 3D environment. A single image is insufficient to fully rebuild the 3D environment due to the loss of information that occurs during photography; at least two separate photographs are required. The foundation of photogrammetry is triangulation, which is the idea that a point's coordinates in all three dimensions are determined by intersecting lines in space. Understanding the camera's location and aiming angles (also known as orientation) for each image in the set is essential for triangulating a collection of points (3).

Photogrammetry is derived from ***three Greek words***

'phos or phot'- photo	Light
'gramma'- gram	drawing
'metrein'-metry	measurement

The science and technique of obtaining accurate information about things in space and their surroundings is known as photogrammetry. It includes registration procedures, measurement, measurement processing and the interpretation of photographic pictures and their results. This is accomplished remotely, using the entire spectrum of electromagnetic radiation and other energy types, without coming into direct touch with the item (4). Projecting a spatial item onto a flat or curved surface using straight lines that originate from the object and meet the surface creates a picture that represents a likeness or depiction of reality. The projection of one point onto another occurs when two points are connected by a straight line. A change in location, size, shape and orientation is referred to as projection, which is a subset of transformation. Assigning matching members from one set to another is another way to think of it as a type of mapping. It is possible to create projections mathematically, graphically, or physically (5).

Sensors are typically used to describe imaging technologies' ability to detect and record radiation. These sensors are part of a procedure called remote sensing, which involves seeing objects from a distance without making direct touch (6). All imaging instruments essentially work by measuring either the distance (range) or the direction. The direction in which the imaging equipment viewed the associated object point, the distance between the device and the object point, or even both dictate how the points are arranged in a picture. Images provide more information than is required for spatial placement alone. The word "spatial" suggests that the location of the data is determined in three dimensions. To be clear, a three-dimensional coordinate system is used to geographically reference this data (7). Time is sometimes seen as the fourth dimension and is as significant. Three distinct data kinds are provided by an imaging device: spectral, geometric and radiometric. To recreate spatial locations, geometric data which are represented by direction and distance shows the spatial association between pictures and object points. Grey-level radiometric data indicates the intensity of electromagnetic radiation that is either reflected or emitted by objects and picked up by sensors. These specifics help identify items and identify their qualitative characteristics. Finally, spectral information, which takes the form of color, shows the main wavelength of radiation that an item emits and is useful for qualitative analysis (5). A comprehensive and wide-ranging study of agricultural systems and their temporal changes at the local and regional levels is made possible by the remotely sensed data (8).

Some drawbacks of photogrammetry include the impact of weather and seasonal conditions. Which can severely limit the collection of primary data; the impracticability of surveying small areas. Higher cost needed for data collection and processing, which necessitates on-site observations for control and analysis verification (5). Some of the clear advantages of on-site data collecting by direct measurement outweigh the aforementioned drawbacks. An picture provides a multilayer dataset with both quantitative and qualitative information, acting as an all-inclusive, real-time record of a scene (9). Additionally, it allows for analysis and processing at a convenient time and place in the distance (10). While direct observations of directions and distances are measured point-by-point, continuous measurements on pictures obtained by tracing or outlining objects are different (5).

Evolution of photogrammetry

The comprehensive evolution of photogrammetry was given in Fig. 1 showcasing the contributions of various pioneers and key developers (11, 12). Among them Aime Laussedat, recognized as the "Father of Photogrammetry"; Edouard Deville, esteemed as "Canada's Father of Photogrammetry"; Carl Pulfrich, acknowledged as the "Father of Stereophotogrammetry"; Earl Church, revered as the "American Father of Photogrammetry"; Duane Brown, credited as the "Father of the short-arc method of geodesy"; and UunoVilhoHelava, known as the "Father of Analytical plotter."

Progression of photogrammetry methods

The historical development of photogrammetry may be divided into four different instances (Fig. 2), each distinguished by methodological and technical developments that increased its adaptability and efficiency (11, 13).

Graphical or plane table photogrammetry

This stage used hand-drawn graphical constructs on a drawing board based on descriptive geometry ideas. Greater precision was achieved with bigger picture formats, which allowed the camera to act as a photographic theodolite. This method was widely used in architectural photogrammetry, especially to record cultural monuments at the Royal Prussian Photogrammetric Institution in Berlin (1885) (13).

Analogue photogrammetry

In the second instance, image geometry was rebuilt using mechanical or optical tools. A 3D model of the thing might be created by aligning two pictures. In this technique, a floating mark may be manipulated by human operators using stereoscopic vision to directly map contour and structural lines (11). Analog photogrammetric equipment achieved great levels of precision due to major developments in optics and mechanics over several decades. One example of the employment of analogue methods in close-range photogrammetry is the stereophotogrammetric plot of Queen Nofretete's bust in the Egyptian Museum in Berlin (13).

Analytical or classical photogrammetry

As computing technology advanced, analytical photogrammetry arose, resulting in the creation of analytical plotters. These photogrammetric methods define the connections between picture points and object points using numerical computations based on collinearity equations. This method helps operators with orientation and restitution procedures, which contributes to its excellent accuracy, adaptability and efficiency (11). The restoration of the skeleton of the Brachiosaurus brancai at the Museum for Natural Sciences in Berlin provides an example of analytical plotters in operation (13).

Digital photogrammetry

In a further stage of development, digital photogrammetry uses computers to determine the dimensions of things that have been photographed. According to Carmen-Mihaela and Adrian-Mihai (4) this procedure usually entails analyzing one or more images using specialist photogrammetry software to ascertain spatial correlations. The use of digital image data makes photogrammetry a specialist field within digital image

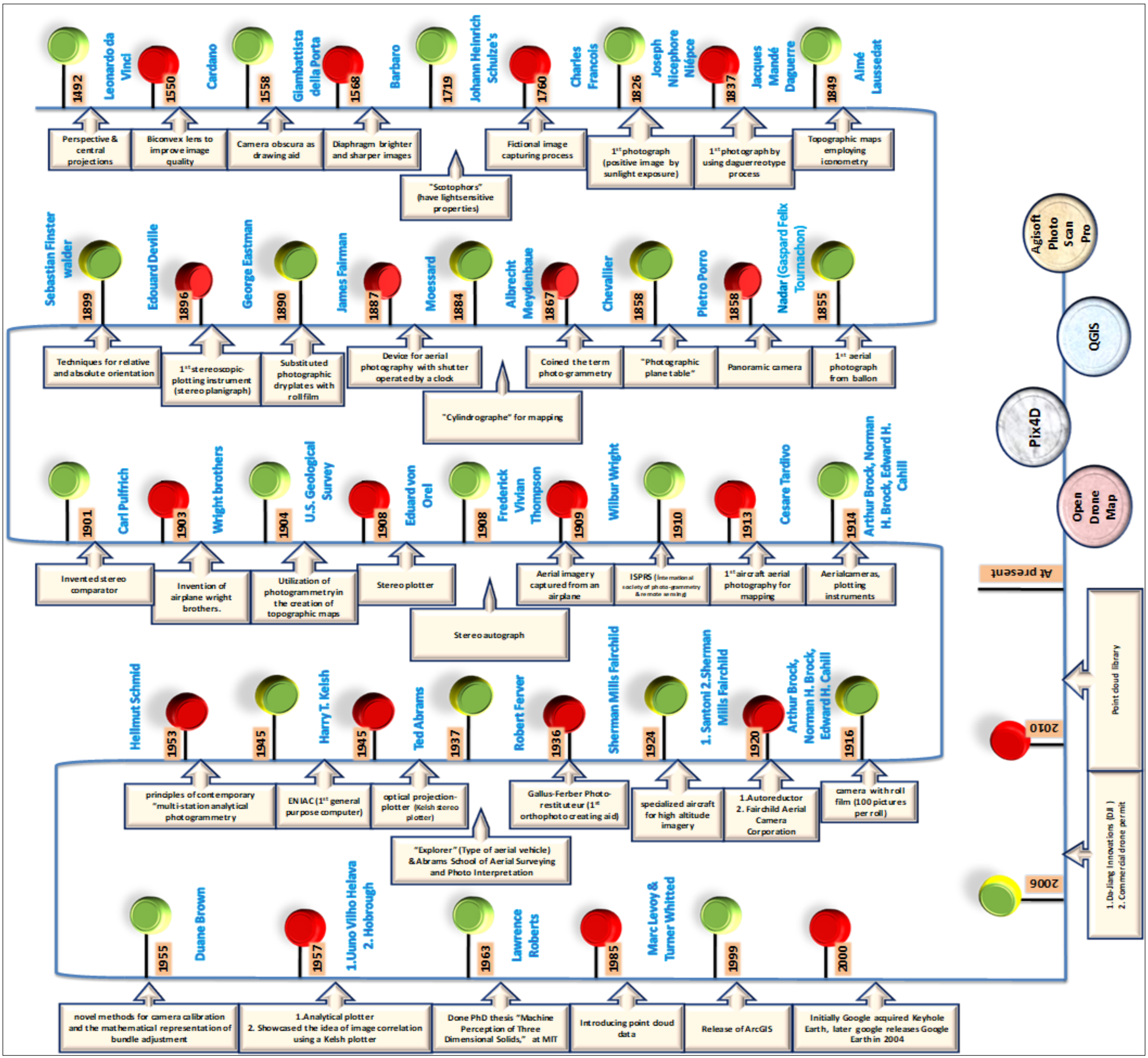

Fig. 1. Evolution of photogrammetry.

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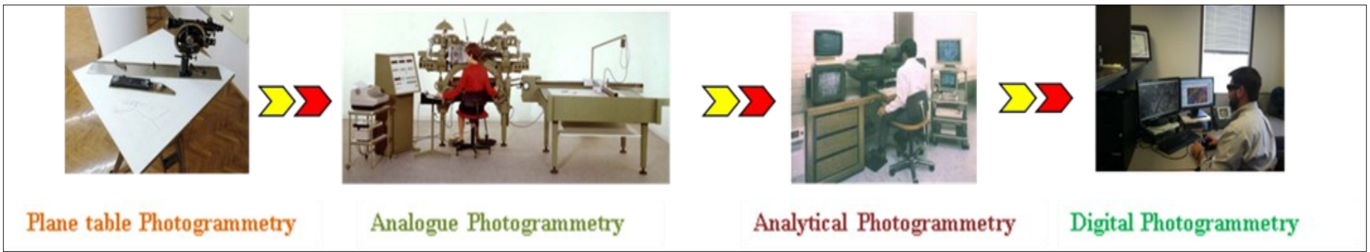

Fig. 2. Progression of photogrammetry methods.

processing. The introduction of digital stereophotogrammetric devices providing significant automation potential and enhanced flexibility (11). Analog and digital pictures can be captured. Analog images are hard copies that are shown on photographic paper or film. Whereas digital images are soft copies that use regularly spaced pixels in a matrix to mathematically capture an object's radiance (5).

Classification of photogrammetry

Photogrammetry is categorized into "three branches" based on the location of the sensor during data acquisition (14). They are terrestrial, aerial and space photogrammetry. This also classified into Interpretative and Metric Photogrammetry.

Terrestrial photogrammetry

In terrestrial photogrammetry, a fixed sensor positioned on the ground is used to capture photographs. In this branch, the camera axis is horizontal or almost horizontal and images are captured from a fixed and usually known point on or close to the ground (Fig. 3). At the moment of exposure, the location and orientation of the camera are frequently measured immediately (5). Such photos are taken using devices such as photo

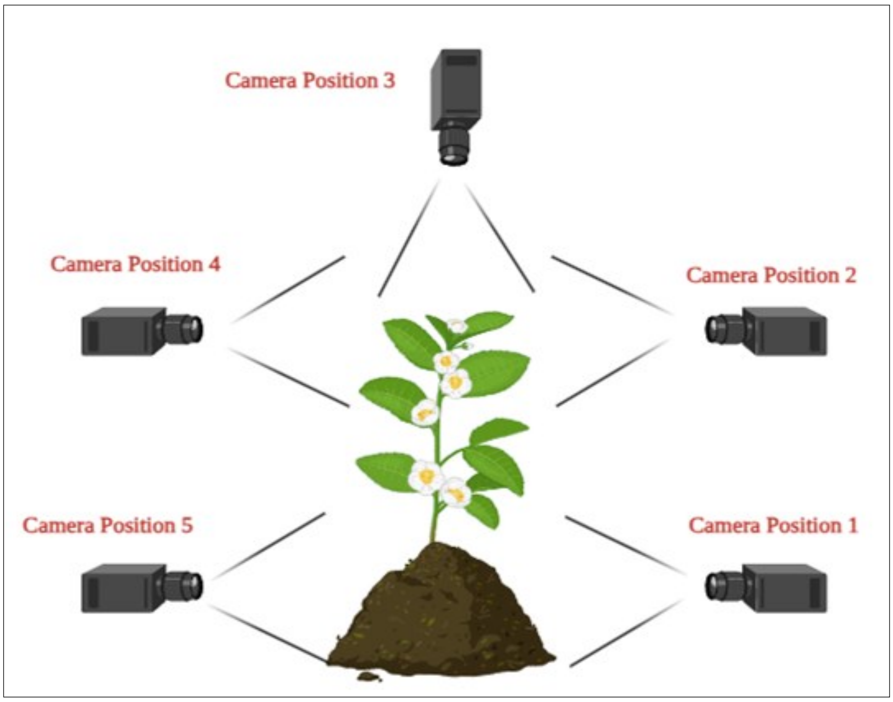

Fig. 3. Terrestrial photogrammetry.

theodolites. A sub-branch of photogrammetry known as "close-range photogrammetry" applies especially to circumstances in which the sensor is close to the item being photographed (5, 15).

Aerial photogrammetry

Aerial photogrammetry is the study of photographs taken by sensors installed on platforms in the air, typically airplanes. A camera with a vertical or nearly vertical axis is used to shoot aerial photos from the air (Fig. 4). As the aircraft follows a flight route, many overlapping photographs are collected and a stereo-plotter is used to analyze the images. Based on the angular direction of the optical axis, aerial photos are further divided into slanted and vertical photos. Low oblique and high oblique photos are two more categories for the later (16).

Photographs taken with the camera's optical axis kept in a true vertical or nearly vertical position are referred to as vertical photographs. It is presumed that the optical axis of such a snapshot is vertical when examining its geometry.

True vertical photograph [v (nadir angle) = 0°]

Near vertical photograph or slightly tilted [v<3°] (5, 17)

Tilted Photograph : Tilted images occur when the camera's axis is nearly vertical, although inadvertent tilting is caused by inevitable aircraft motions. A photograph is categorized as vertical if the tilt is less than 3°; if it is greater than that, it is categorized as slanted or oblique. Low oblique and high oblique photos are two further classifications for tilted photos (18). Compared to vertical images, oblique photographs cover a far greater area.

High oblique photograph (v>70°, horizon visible): A high oblique photograph is one where the apparent horizon is visible. The apparent horizon is the line where the earth seems to meet the sky from a specific point.

Low oblique photograph (v≥3°, horizon not visible): This type of photograph does not display the apparent horizon.

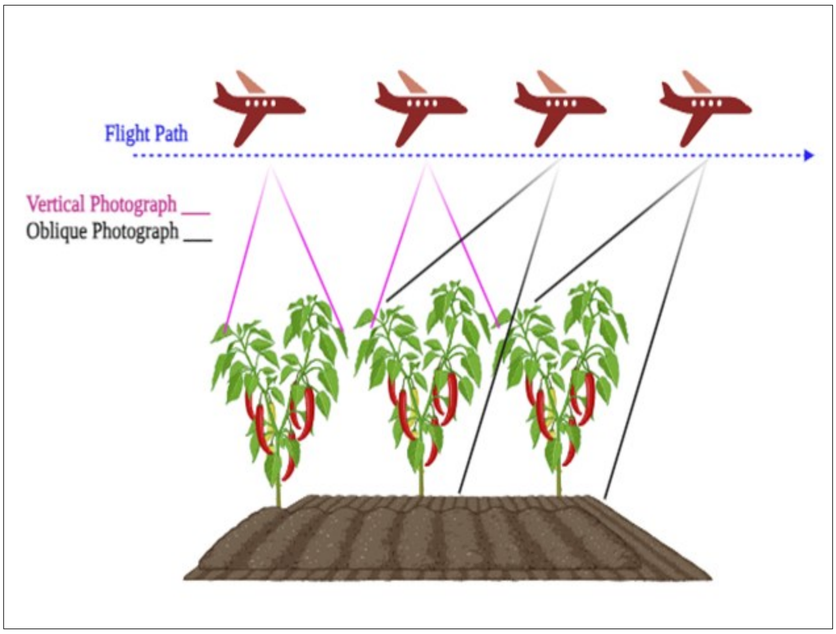

Fig. 4. Aerial photogrammetry.

Convergent photographs are a pair of low oblique images taken sequentially along a flight direction, covering essentially the same area (5, 17).

Space photogrammetry

Processing satellite photos of the earth or other planets is known as space photogrammetry. It includes all facets of photography and measuring from space, regardless of whether the camera is fixed on Earth, housed in a man-made satellite, or placed on a planet or moon (19).

Principles of photogrammetry

Understanding how human vision works is the foundation of photogrammetry's fundamental ideas. The lens of the eye essentially functions as a convex lens, creating a picture of an object on the retina that is inverted. The optic nerve then sends this reversed image to the brain for interpretation (3).

Monoscopy

The process of seeing with only one eye is called monoscopy. It gives a two-dimensional depiction of the scene without depth awareness. Though the picture created on the retina contains a multitude of information (20).

Stereoscopy

The visual process that uses both eyes at once is called stereoscopy. This enables the brain to interpret the two pictures created on the left and right retinas to perceive the third dimension in a scene (20, 21).

Parallactic angle

The rays emanating from a scene are not graphically represented by the human brain. Rather, it examines the angle that each eye perceives between the two light beams that emanate from a single object. "Parallactic Angle or Parallax" is the name given to this angle (22). The parallactic angle increases with distance from the eyes, decreasing with distance from the eyes (3).

Triangulation

A basic technique used by theodolites and photogrammetry to get 3D point measurements is triangulation. This technique uses the mathematical intersection of convergent lines in space to pinpoint a point's exact position. One significant way that photogrammetry differs from theodolites is that it may measure several points at once without having a restriction on the total number of triangulated points. To create a line from each theodolite in the theodolite context, two angles must be measured (3).

The distance between the focal plane, which is typically the film and the center of the camera lens is known as the focal length (3).

The ratio between two points' real distances on the ground and their distances in a picture is known as scale (3).

Rebuilding a stereoscopic model from two photos acquired from various perspectives is known as stereoscopic restoration. The equivalent picture is seen by each eye, producing a three-dimensional impression. To see and examine stereoscopic pairs of photos, a variety of tools are used, including optical stereoscopes, anaglyphs, polarization and digital stereoscopes.

Optical stereoscope enables the observer to perceive a 3D effect by presenting each eye with a slightly different image taken from different perspectives (16).

Anaglyph utilizes special glasses with two complementary colors (e.g., cyan and red), allowing each eye to see only one of the two images (16).

Polarization involves special glasses with different polarizations (e.g., horizontal and vertical), to see corresponding image (23). An author used this technique to differentiate agricultural crops (24).

Digital stereoscopes are also known as digital stereo viewers or stereo display. Unlike traditional optical

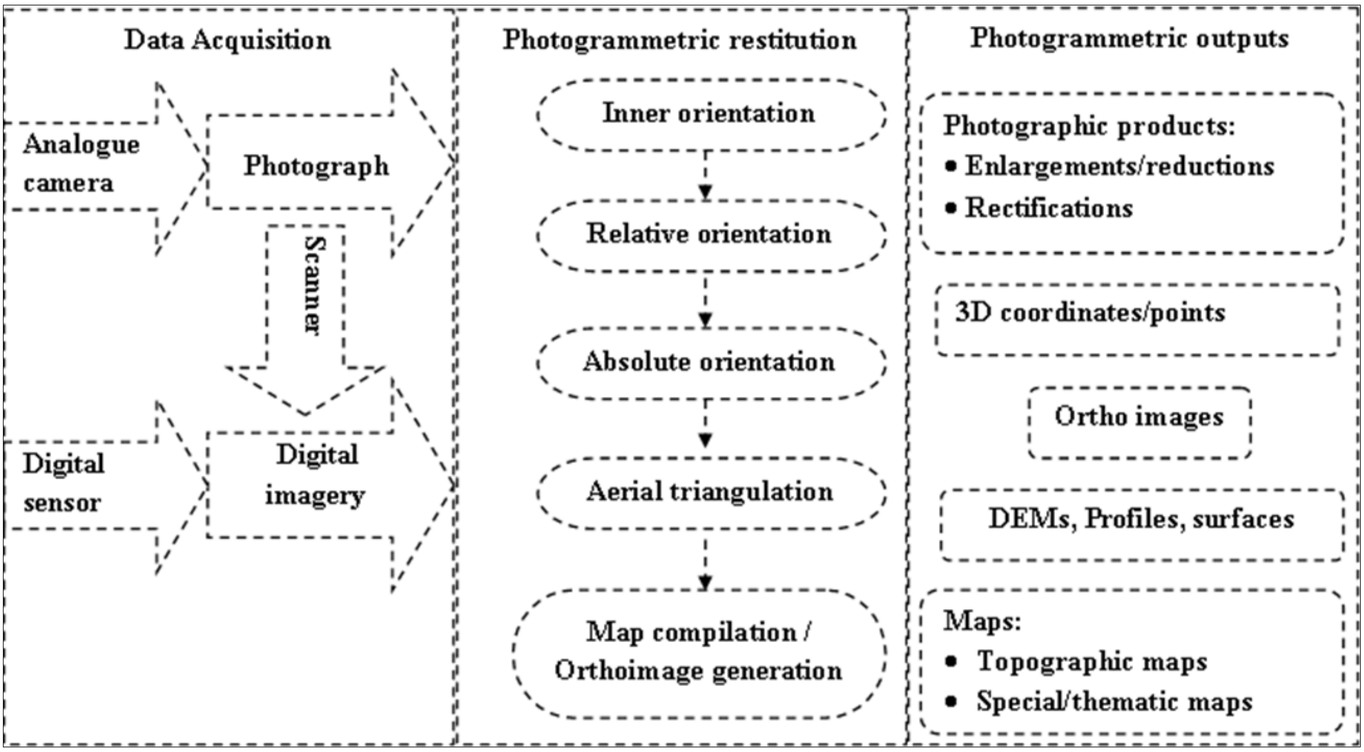

Fig. 5. Procedure for photogrammetry (Modified from 17).

stereoscopes which use physical lenses and prisms, digital stereoscopes leverage electronic displays to present separate images to each eye, creating a sense of depth (16).

Devices (Platforms) and detectors (Sensors) used in photogrammetry

Types of devices

Photogrammetry can be categorized into three primary groups based on the proximity between the capturing device's position and the object of interest during image acquisition (11).

Land-based platforms/terrestrial platforms/surface-based platforms: Which include a wide variety of instruments such portable devices, tripods, towers and cranes, are essential to remote sensing and photogrammetry. These tools are frequently used to evaluate the characteristics of sunlight and conduct close-up analyses of items at close range. For instance, these kinds of equipment are most effective when analyzing a single plant or a tiny patch of grass (25).

Airborne/aerial platforms/atmospheric platforms: They are mostly made up of balloons, airplanes and UAVs (unmanned aerial vehicles), with helicopters being used sometimes. These aircraft are used to collect data and take incredibly detailed pictures of any area of the world at any time (26).

Space-based platforms/ orbital platforms/celestial platforms: Satellites or space shuttles are occasionally used to identify objects. The Space Shuttle is a unique reusable spacecraft that can be used for a variety of missions and functions as a satellite (25). Based on their time and orbital arrangement, satellites may be divided into three groups: geostationary, equatorial and sun-synchronous orbits (27).

Types of detectors

Based on illumination source sensors are classified into *passive and active sensors.*

Passive sensors use solar energy as the main source of radiation. To detect natural light that is either reflected or emitted from surfaces and objects (Fig. 6a). It's critical to have accurate measurements of the amount of solar energy that reaches the surface during the observations when using data from passive sensors. By using this information, atmospheric impacts may be corrected and the final data or photos will more closely reflect the surface's true properties. Photographic cameras, electro-optic radiometers and passive microwave systems are a few types of passive sensors (28).

Active sensors, such as lidar and radar devices, initiate the detecting process by releasing energy from their own source (Fig. 6b). After the energy interacts with a surface, these sensors then measure the energy that is returned. Active optical (lidar) and active microwave (radar) systems are particular instances of active sensors (28).

Based on data format, sensors are classified into *imaging and non-imaging sensors*

Imaging sensors: By processing the data gathered by image sensors, a comprehensive picture of a region may be created. It enables the visual resolution of smaller areas within the sensor's overall view. Depending on the geographic resolution and sampling of the data, picture data may be used to analyze spatial connections, object forms and physical size estimation. When spatial information is mapped out, image data is especially useful (Fig. 6c). Tone, color, patterns, texture, size, form and object connections are just a few of the elements used in image interpretation. Which frequently blends visual and digital methodologies. Radar, thermal and optical imaging sensors are a few types of imaging sensors (28, 29).

Non-imaging sensors: These are usually portable instruments that capture a single response value or data point. Which do not have the finer resolution necessary to produce an image from the whole region that was examined. Although the spatial resolution of the sensor may cover a tiny region, these discrete values are sometimes referred to as point data (Fig. 6d). Spectrophotometers, radiometers and laser rangefinders/ altimeters are a few types of non-imaging sensors (30).

Photogrammetric software's in agriculture

The use of photogrammetry in many different industries has significantly increased in recent years. The capabilities and operation of components used in picture processing inside photogrammetry stations have been greatly improved by advances in computer technology, particularly high-performance processors. To make photogrammetric procedures easier, a variety of software programs have been created (31). These software applications are categorized into *payment and free software.*

Payment software can be purchased as licensed packages that are designed for certain tasks like calculating vegetative index, processing and interpreting images, or creating ortho-mosaics. Although using licensed software necessitates high-performance computers. It comes at a significant financial expense. It provides the freedom to do independent research whenever desired.

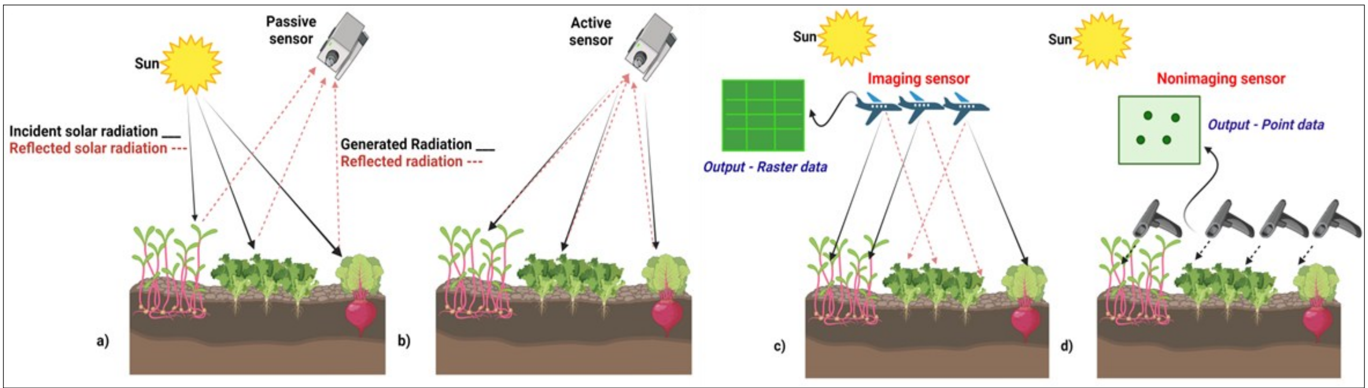

Fig. 6. Types of detectors (Sensors).

Here are some notable instances of licensed software and their specifics:

» Agisoft LLC in St. Petersburg, Russia, developed AgisoftPhotoScan. A program for processing aerial photos that allows for the creation of 3D information and high-quality digital image processing. It is appropriate for photogrammetric documentation in a variety of disciplines, including architectural structures, archaeological sites and agriculture (32-34).

» Pix4D is a cartography producing tool that uses pictures from lightweight cameras that are carried by UAVs. able to handle up to 10000 RGB, infrared, or thermal photos at once and process images with resolutions ranging from 1 to 200 megapixels. To use this program, the photos must have accurate position information. The creators worked with Parrot to produce Pix4Dmapper Ag; a proprietary program designed specifically for precision farming. With this version, multispectral photos are transformed into maps intended for particular crop management and agricultural analysis (35).

» Ensomosaic, a product of MosaicMill, is used to create ortho mosaics without distortion in regions with notable topography undulations. Furthermore, there is a specific version made for agriculture called Ensomosaic Agri (31). This version has great efficacy in NDVI and has features like vegetative index computations (36). UAV licenses are available from Ensomosaic, enabling the taking of an infinite quantity of pictures.

Free software choices are available; however, they frequently rely on Cloud-based processing systems that charge fees based on the amount of data to be processed. Although users of free software could have to pay for certain activities. This option might be preferable than licensed alternatives for low-complexity and infrequently executed jobs (37). The following is a list of notable free software programs and details:

» OpenDroneMap is an open-source toolkit that provides a complete photogrammetric solution that is especially made for tiny UAVs (drones), balloons and kites (38). Using this program, highly overlapping unreferenced data may be processed to provide a variety of outputs. This includes colorized point clouds, digital surface models (39), textured digital surface models and orthophotography (40). Notably, the orthophoto produced by OpenDroneMap's image processing may be seen online via WebODM and on other platforms like Meshlab and Python.

» Insight3D is a program that aligns common spots in many images collected from different perspectives to create 3D orthophotos (41). The software uses the camera's optical characteristics to calculate spatial locations. It’s incapacity to manage several photos at once. However, it stems from the substantial memory resources required to store every image feature for high-resolution calibration. Furthermore, it is unable to convert point clouds into the actual coordinate

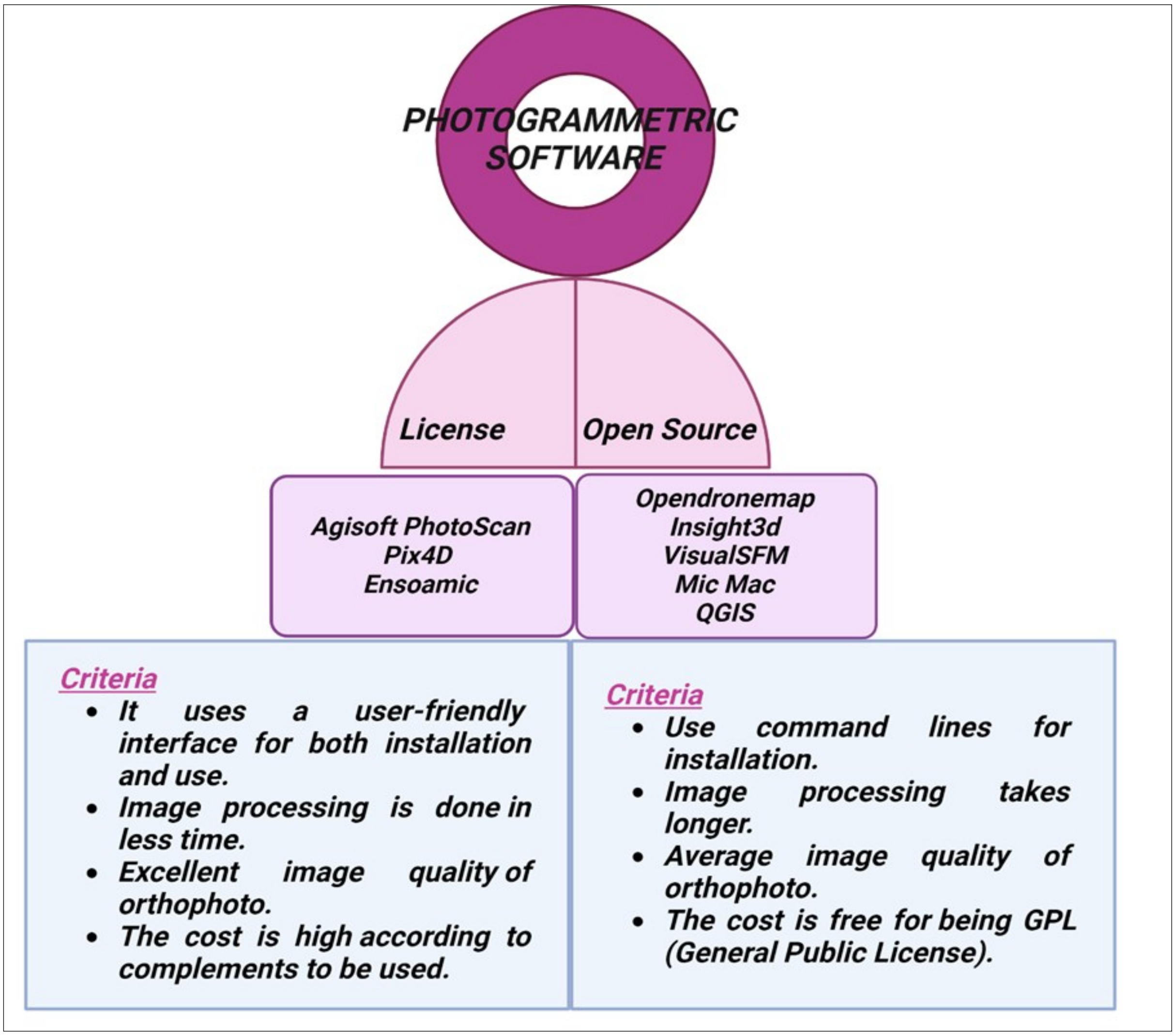

Fig. 7. Criteria for photogrammetry software (Modified from 31).

system, Which means that other free programs must be used to convert coordinates (31).

» A graphical user interface (GUI) program called VisualSFM makes it possible to employ Structure from Motion (SFM) to create a 3D point cloud. Simple dots with RGB values and XYZ spatial coordinates make up these point clouds.

» Marc Pierrot Desseilligny created Mic Mac, which focuses on producing depth maps from a set of pictures that are grouped around a master image (31). A picture in which every pixel represents the relevant depth with respect to a certain point of view in relation to an image or master scene is called a depth map. Like other photogrammetric tools, Micmac is based on epipolar geometry (stereoscopic vision geometry) although it does not offer multi-stereoscopy (42). This feature makes it especially well-suited for "quasi-planar scenarios," such as reliefs, facades and landscapes. Although it might not be as good at handling circular bundle-type items or artifacts.

» QGIS, a distributed agricultural monitoring system from Ukraine, is made to work with SQLite databases and makes it easier to create vectorized field maps. With support for several data types and providers, this program focuses on handling geographic data. It offers two ways to calculate indices: radiometric indices that comprise commonly used vegetative indices in contemporary agriculture and the Raster Calculator, which permits the inclusion of particular formulas (31). The above-described softwares' require some criteria to work on that criteria are illustrated in Fig. 7.

By contrasting the features of licensed and free software alternatives, Table 1 lists the main features of many photogrammetric programs. Interestingly, a lot of open-source software is devoid of characteristics that are necessary for efficient photogrammetric use. In contrast, Open-DroneMap is a free program that provides around 90 % of the features of its licensed competitors. Which makes it especially appropriate for image processing in the context of this study by Delgado-Vera (31). The following are the main characteristics of photogrammetric software:

To attain a more accurate picture correction, the triangulation process involves both interactive measurement of control points and automated measurement of union points (43).

Cloud generation is an automated procedure that uses correlation algorithms to link homologous spots between photographs, producing more realistic-looking three-dimensional images (44).

Each pixel in the "Raster" file created by exporting to MDT/MDS format comprises XYZ coordinates in relation to the topography of the landscape. The MDT/MDS format makes it possible to see infrastructure, vegetation and other things.

All submitted photographs are combined into a huge, high-resolution snapshot using Orthomosaic Production, which displays the blending of orthogonal sections across the collection.

The resulting stereoscopic model is subjected to error control using Check Points, which are points having XYZ, XY, or Z coordinates (45).

Multispectral imaging is a technique that uses a camera equipped with a miniature multispectral sensor to take pictures in different spectral bands. In addition to surface and volume calculations for the reconstructed 3D model, it is important to photogrammetric software allows distance measurements in the model (31).

Image handling

Photogrammetry is an extremely powerful and adaptable measurement technique. That may be used on a variety of surfaces, such as land, sea, air and even space and on objects of all sizes. Its use cover both completely and partially overlapping measures, demonstrating its versatility and adaptability in a variety of contexts and scales.

Types of measurements in photogrammetry

Complete and partial overlapping measures are the two basic categories of measurements. Overlap, represented as a percentage, is the degree to which one image encompasses the area covered by another. A typical picture survey has 30 % lateral overlaps (among photos on neighboring flight paths) and 60 % forward overlap (among photos along the same flight path). Fig. 8 shows various instances of overlapping measurements. The common line just acts as a pivoted point, connecting the two panels but allowing for different angles between them. Fig. 8a illustrates no overlap case, Fig. 8b shows an inadequate overlap case and Fig. 8c displays a hinge effect. Therefore, the overlap must cover at least two dimensions and not just a line of points. The "hinge" effect is the name given to this phenomenon. Fig. 8d showed sufficient overlap cases, whereas Fig. 8e showed total overlap cases (3).

Image processing

Photogrammetric processing is a branch of image processing that involves the methodical transformation of photographs from aerial, space and ground-based platforms that record the earth's surface. By correcting distortions caused by terrain relief, tilt angles of aerial photography, atmospheric interference and other aberrations inherent in picture capture. This transformation seeks to provide a predefined projection.

Table 1. Comparison of photogrammetry software (31)

Feature	Pix4D	Agisoft Photos Can Pro	Ensoamic	Open Drone Map	Insight3D	VisualSFM	MicMac	QGIS
Triangulation	✓	✓	✓	✓	✓	×	✓	✓
Point cloud	✓	✓	✓	✓	✓	✓	✓	✓
3D models	✓	✓	✓	✓	✓	✓	✓	✓
Export MDS/MDT	✓	✓	✓	✓	×	×	✓	✓
Ortomosaico exportation	✓	✓	✓	✓	✓	✓	✓	✓
Measurements	✓	✓	✓	✓	×	×	×	×
Checkpoints	✓	✓	✓	✓	✓	×	×	×
Multispectral Images	✓	✓	✓	✓	×	×	✓	×
Real-time display	✓	✓	✓	✓	✓	✓	✓	×

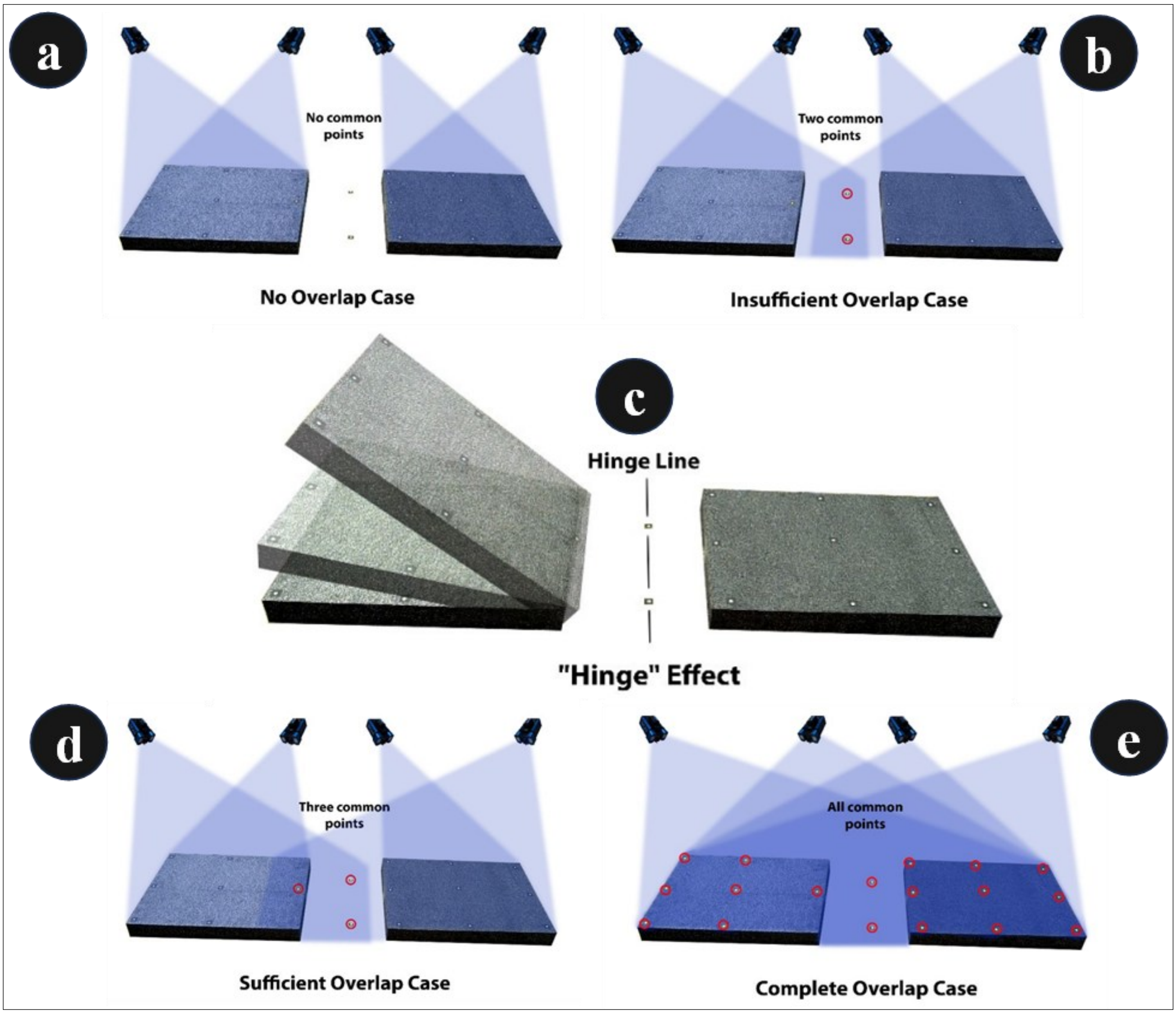

Fig. 8. Different types of measurements (Modified from 3).

Photogrammetric processing carefully corrects these aberrations to guarantee the integrity and precision of the final imagery, enabling improved interpretation and analysis in a variety of applications (18, 19, 46).

Geometric correction and Georeferencing: Geometric corrections are the process of correcting an image's spatial representation to precisely depict its position on the surface of the Earth. Contrarily, georeferencing entails matching an image or map to exact geographic coordinates in the actual world to guarantee its correct placement in space. Enhancing the precision and spatial alignment of images with actual geographic coordinates requires both procedures (19).

Reference Coordinate Systems: Geographic coordinate systems, which depend on latitude and longitude and geodetic coordinate systems. Which are based on map projections, are the two main categories of coordinate systems for geographic data (47). National map projection systems, arbitrary local coordinate systems and geographic coordinates expressed in decimal degrees or degrees, minutes and seconds" are examples of frequently used coordinate systems (48).

Image Rectification: Lens distortion, picture tilt and relief displacement can all result in image distortion. Orthorectification and polynomial rectification utilizing ground control points are two techniques for resolving these distortions (19).

Image Mosaics: It can be necessary to take several pictures of a certain location in order to gather precise information. Which are then put together to create an image mosaic. The method of combining adjacent photos to create a single image file is known as mosaicing (49).

Image enhancement: Resolving issues like chromatic aberration, noise and vignetting that might deteriorate an image's quality is part of image enhancement (19). Radiometric faults can be reduced or eliminated by utilizing camera or professional image-editing software to partially or fully repair these errors. However, the items themselves might also have poor image quality, especially when it comes to color contrast. Techniques for enhancing images range from minor tweaks to drastically changing the visual look to draw attention to particular details (48).

Correcting Lens-Dependent Aberrations: Lens-related aberrations appear as circular effects that are centered on the optical center of the picture. Prior to cropping or distorting the image, it is imperative to correct these aberrations. Vignetting strength is not a fixed effect since it depends on variables such as exposure, aperture and lens parameters (50).

Contrast Enhancement: By enhancing the intensity difference between objects or areas, this technique seeks to improve the visibility of picture details. Histogram equalization, local contrast enhancement and dynamic range modification are methods for enhancing contrast (51).

Image Filtering: This technique uses neighborhood operations to recalculate each pixel's value by taking into account the values of the pixels that surround it (52). By reducing noise and enhancing picture details, this method eventually raises the quality of the image as a whole.

Image transformations: To provide an alternate representation of the data, image transformations entail processes that reinterpret the information contained in an image. Then generating a new collection of image components (53).

Image Ratios and Vegetation Indices: To enhance spectral fluctuations and decrease brightness disparities, an image ratio divides pixel values from one image band by matching values in another band (48). This method is valuable for distinguishing features with subtle color discrepancies and reducing the shadowing effect in sunlit scenes, commonly known as the topographic effect. Vegetation indices play a crucial role in monitoring changes in both crops and forest vegetation. By enhancing the ability to forecast, alleviate and adjust to shifts in vegetation patterns can derive parameters such as 'leaf area index, green biomass and chlorophyll content, while mitigating the effects of shadowing and illumination variation' (19, 54).

Principal Components Analysis (PCA) and Color Space Transformations (CST): In multispectral and hyperspectral imaging, PCA is used as a data compression technique that maximizes the amount of information retained in the original image while reducing the number of new components. Furthermore, CST offers an alternative viewpoint on color representation and perception by transforming the picture from the RGB (Red, Green and Blue) color system to the HIS (Hue, Saturation and Intensity) color space (19, 48).

Image classification: Pixel values in digital or scanned analog photos are obtained from spectral reflectance measurements made by sensors or film. Which provide comprehensive quantitative information on the spectral properties of objects or surfaces that are shown. Usually, 8 or 12 bits per band are stored (18, 19). While spectral reflectance color is essential for differentiating between different forms of ground cover, other elements including shape, size, pattern, texture and context also play a key role in feature recognition (48). Techniques for classifying pictures are used for both qualitative and quantitative image analysis. Supervised and unsupervised classification are the two main techniques used to categorize photographs (55). To categorize pixels or objects in an image, supervised classification uses computer methods (such as Maximum Likelihood Classification, Support Vector Machines, Random Forests and Convolutional Neural Networks) that have been trained on preset classes (56). Unsupervised classification, on the other hand, does not require a labeled training dataset; instead, algorithms such as K-Means Clustering, Hierarchical Clustering and Self-Organizing Maps may find patterns or groupings within an image without any prior class information (57). Additionally, other classification techniques include Object-Based Image Analysis, Decision Trees and Fuzzy Logic Classification.

Stereo viewing, often known as stereoscopy or stereovision, is a technique that uses two slightly shifted 2D pictures to replicate 3D depth perception. The human visual system perceives depth and spatial connections of things by making use of the differences between these representations. Stereo pairs, binocular disparity, cross-eyed viewing, anaglyph and polarized 3D glasses, auto-stereograms and digital stereoscopes are among the several methods (58).

Applications for photogrammetry in agriculture

Images are a potent way to get extremely accurate 3D data at different sizes. Both 2D and 3D metric data may be extracted from digital photos using photogrammetry techniques (59). A number of programs that can create 3D point clouds from RGB photos have surfaced in recent years (60). Furthermore, improvements in computer vision, an area that is undergoing extensive research, are closely related to advances in photogrammetry, indicating that photogrammetric skills are continuously evolving and improving (61). The capacity of photogrammetry to generate incredibly realistic 3D models and provide surface color information is one of its noteworthy strengths (62). Numerous industries, including industrial metrology, architectural, medical and forensic imaging, successfully use photogrammetry (63). Fig. 9 illustrates how photogrammetric techniques have become more popular in agriculture in recent years. According to a report, photogrammetry has been used in research projects (59). To precisely measure grassland yield, photograph tomato plant exteriors, detect apples and determine their 3D locations, measure leaf length and rosette area and characterize canopy architecture in olive trees (59, 62, 64, 65). In forest science applications, it was developed a cost-effective continuous terrestrial photogrammetry system with real-time kinematic correction. To acquire georeferenced, accurate point clouds of forests (66). While it was estimated diameter at breast height from a point cloud generated using an uncalibrated handheld camera (67). It was tested the effectiveness of "structure-from-motion combined with multi-view stereo-photogrammetry" in producing accurate 3D point cloud models. Which made it easier to estimate linear metrics and tree volume (68).

According to Aasen, hyperspectral data is a potent instrument that provides information on a number of topics, including the biophysical and biochemical characteristics of crops and flora. With the advent of light hyperspectral snapshot cameras, each exposure's spectral information may now be recorded in a 2D picture. By using specific procedures based on photogrammetric algorithms, surface topography may be reconstructed in three dimensions. This allows for the simultaneous extraction of spectral and structural information (59). Given its strong relationship to basic plant characteristics and interactions with the environment. It is critical to study plant geometry, which includes "size, volume and shape," as well as structural elements like "leaf density, leaf area index, canopy porosity, woody structure and training system" (69). This thorough knowledge of plant geometry makes it easier to estimate crop output, water consumption, tree biomass and long-term productivity (59). Accurate commercial-scale 3D crop characterization was difficult, if not impossible, until the advent of 3D characterization sensors. However, this procedure has been transformed by modern sensor devices,

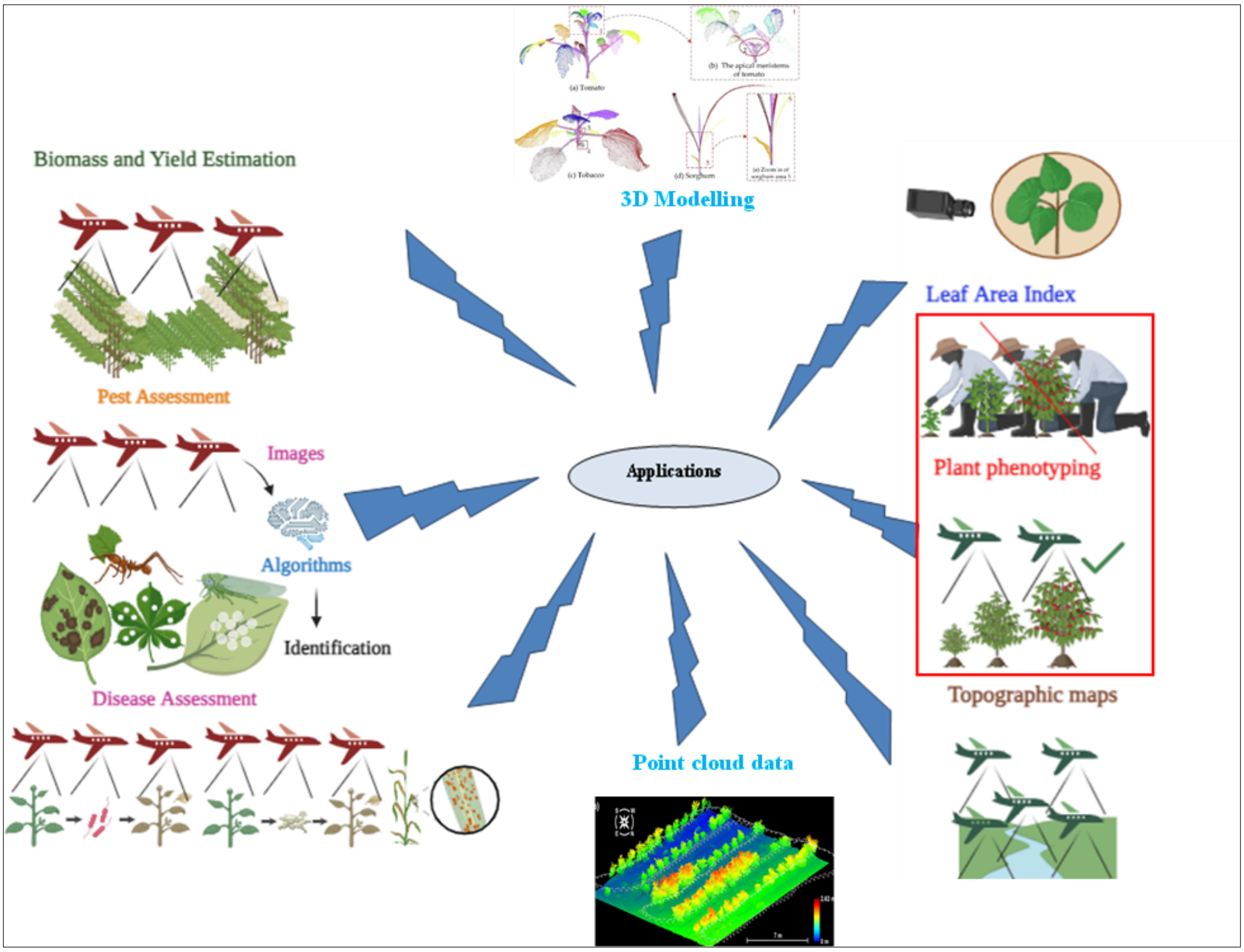

Fig. 9. Applications of photogrammetry in agriculture.

making 3D canopy characterization very easy and quick. Digital photogrammetric approaches, linear arrays of light sensors, stereo vision and LiDAR (Light Detection and Ranging) sensors are the main 3D techniques used in agriculture (70). Because they provide non-destructive methods of monitoring throughout time. These technologies have great potential for supporting longitudinal research and analysis (71).

UAVs equipped with imaging and non-imaging sensors have a number of uses in agriculture. Starting from field testing and research, biomass assessment, crop growth monitoring and food quality assessment (72). According to other studies, they also make precision farming easier by allowing site-specific herbicide treatments depending on weed density (72, 73). This lowers fungicide consumption through targeted application in potato production. It was evaluated plant height and Leaf Area Index (LAI) in maize using oblique and nadir photos taken by UAVs (74). Plant height and LAI must be accurately and quickly retrieved for a variety of agricultural applications as these are crucial markers of crop development and yield (75). Throughout the growth cycle, it was found that manual measurements and nadir and oblique photographic measurements of plant height agreed well. On the other hand, oblique photography produced better LAI estimations than nadir photography. Furthermore, compared to nadir photography, oblique photography produced more detailed 3D depictions of plant architecture and vertical leaf area distribution, two important variables affecting yield (74). Compared to nadir photography, the point clouds produced by oblique photography were much bigger. To estimate canopy height and LAI in sorghum plants, a comparison between RGB photogrammetry and UAV LiDAR was conducted (75). Accurate measurements of canopy height extraction and biomass prediction were made possible by extensive 3D insights into plant canopies. It is provided by both LiDAR and RGB photogrammetry point cloud data. When compared to RGB photogrammetry, UAV LiDAR demonstrated better accuracy and penetration capabilities into the canopy. Photogrammetry showed a trend toward underestimating at higher canopy heights, despite the fact that both methods produced consistent findings with high R^2 values (75).

Photogrammetry is employed well in agriculture to detect and count individual plants. It was identified corn plants with high precision by employing computational geometry and machine learning tools (76). UAV imagery used to generate canopy height models by employing Voronoi data moles. Similarly, it was integrated enhanced feature fusion and multi-scale attention mechanisms with deep leaning models to achieve higher precision (77). In maize, it was used to support vector machines and neural networks to quantify plant counts (78). It was calculated canopy height in buckwheat fields using photogrammetric software and aerial stereo photos (79). Using two pictures and marker coordinate data, Digital Surface Models (DSM) were produced using Image Master Photo Ver. 2.4. In comparison to eye evaluations, the study found that the aerial picture system and photogrammetric analysis greatly improved the quantitativeness, objectivity and precision of canopy height measurement. Which in turn improved the evaluation of lodging rates. Interestingly, compared to higher altitude photography, lower altitude photography produced better accurate data for analysis. With point cloud data from either LiDAR or RGB photogrammetry providing thorough 3D canopy information and reduced sensitivity to spectrum difficulties in thick vegetation. These methods are essential for high throughput phenotyping and sustainable field management (80). Prior research has shown that UAV-based RGB photogrammetric point clouds are useful for biomass estimate, LAI and canopy height extraction (81).

UAV based 3D reconstructed images were widely used for estimation of biomass. In their study of the Halberd cultivar of bread wheat (*Triticum aestivum* L.), it was found that estimations of canopy height and Harvest Index (HI) obtained from point clouds corresponded favorably with hand observations (60). For plant breeding and research, biomass estimate from as little as 48 photos per plot proved appropriate. The association between HI and Point Cloud Volume-based HI (PCV-HI) was examined using linear regressions. Which showed a significant positive correlation. Likewise, a noteworthy association was noted between Above Ground Biomass (AGB) and point cloud volume. Strong correlations were also found when manual height and Point Cloud Height (PCH) were compared to AGB and PCV; PCH showed somewhat larger correlations with AGB and PCV than canopy height. To enhance oilseed, point cloud segmentation and biomass prediction, a report used techniques like 3D gaussian splatting and segment anything model (82). UAV based canopy volume and fresh AGB were derived from point cloud volumes in forage crops with higher correlation with ground data. To improve precision of biomass estimation models, feature augmentation (FA) techniques like linear regression-based FA was used (83). It was highlighted that the fusion of multiple sensors (RGB, multispectral and hyperspectral images) derived textural and structural information's with random forest models to improve accuracy of millet biomass prediction (84).

In order to measure soil surface roughness (SSR) characteristics across agricultural soils, it was evaluated the use of Structure from Motion (SfM) and Terrestrial Laser Scanner (TLS) photogrammetry techniques (85). According to the study, tillage has a major impact on soil roughness in agricultural soils. Which can have both directed and random components. Analysis of DEM and evaluation of multidirectional roughness characteristics showed how well TLS and SfM photogrammetry methods work together to assess SSR. These techniques provide a wealth of 3D data, enabling detailed examinations of surface roughness directionality, which is important for processes like microwave scattering and soil and hydrological erosion. Table 2 included further uses of photogrammetry in agriculture.

Agricultural watersheds endure persistent microtopography alterations as a result of intense agricultural operations. Which have a substantial impact on the measurement of runoff and sediment transport dynamics. For a more thorough comprehension and evaluation of these processes, precise and high-resolution 3D reconstructions of these watershed regions are essential (86). A study assesses how well TLS and UAV photogrammetry work together to gather topographic data in a limited watershed region (86). The findings show that TLS scanning and UAV photogrammetry produce the most precise data, with each technology exhibiting unique advantages and disadvantages. The study emphasizes how crucial it is to choose the right technology for data collecting. Furthermore, DEM accuracy is impacted by elevation variations linked to mustard fields, underscoring the impact of vegetation on elevation measurements.

UAVs are used in forestry and nature conservation for a variety of purposes, including detecting forest fires, monitoring for compliance with legal regulations, identifying harvest sites, overseeing forestry operations and surveillance for adherence to legal regulations, as well as gathering evidence in the event of violations or infringements (87). They are especially useful for tracking and identifying changes in natural forests when it is difficult or undesirable to enter sensitive or inaccessible regions (72). A study in which they used RGB photos and stereo

Table 2. Applications of photogrammetry in agriculture

Crop	Utilized for	By using	References
Arabidopsis thaliana	Plant phenotyping	Novel photogrammetry and computer vision algorithms	(62)
Tomato	3D modeling	Close-range photogrammetry	(64)
Maize	3D architecture of canopy	Stereovision (Stereo plotting technique)	(64)
Weeds (*Xanthium strumarium* L., *Datura ferox* L., *Sorghum halepense*)	3D modeling	SFM and MVS	(92)
Cauliflower	Discriminate crops and weed	Kalman filter (tracking algorithm)	(64)
Tobacco	Nitrogen and Potassium deficiencies	SFM and MVS	(93)
Grapevines	Detection of affected or missing plants	SfM used to develop DSM	(94)
Grapes	Canker disease identification	Image analysis	
Cotton	Symptoms of plant diseases (spots, stains or strikes)	Support Vector Machine classifier	
Beetleaves	Different leaf spots detection (*Cercosporabeticola, Ramularia beticola, Uromycesbetae, Phomabetae* and the *bacterium Pseudomonas syringaepv. Aptata*)	Statistical features classifier	(95)
Tobacco	Anthracnose		
Apple	Apple scab	Scion image processing and statistical analysis	
Phlox	Powdery mildew		
Canadian golden rod	Rust		
Greenhouse plants	Pest detection	Binocular stereo vision technique	(96)
Vineyards	Pest (*Jacobiascalybica)* affected plants	Computational vision algorithms (artificial neural network) combined with geometric techniques (consumer-grade cameras)	(97)
Wheat	Detection of crop cover and yield estimation	Spectrograph	(98)
Apple	Fruits detection	Combination of instance segmentation neural network and SFM	(65)

photogrammetry techniques to create a 3D model of a real defoliated fruit tree (59). UAVs are useful in forestry and wildlife conservation for several reasons. With a bias of -0.15 mm for diameters and 0.05 mm for lengths, a 3D point cloud that faithfully depicted reality was produced utilizing methods such as "SfM and Multi-view Stereo". Furthermore, the approach recognizes the significance of dehydration and may spot variations in trunk and branch diameters. Additionally, dehydration-induced branch deformations, providing insightful information for forestry and agronomy study (59). To estimate the tree row volume of a super-high-density olive orchard, it was compared traditional approaches with UAV photogrammetry and 3D modeling technologies. Their findings suggested that close-range photogrammetry from UAVs exhibits good accuracy in forecasting tree row volume with low labor time. The need for qualified staff to use the technology efficiently has been regarded as the main drawback (88). Accurate measurements can be made using photographs, photogrammetry is a flexible method for creating point clouds from both ground-based and UAV-captured imagery. When it comes to creating DSMs for forestry research and agricultural field trials photogrammetrically produced point clouds have shown themselves to be a highly effective substitute for LiDAR. These models have demonstrated success in estimating canopy height and have been effectively utilized as predictors for above-ground biomass assessment (89, 90).

Farmers are using precision agriculture more and more to improve field management (91). In addition to regular visual photographs, researchers have created a camera system that can record thermal images. Combining these photos yields useful information for identifying immature fruits and identifying regions of the land that need more care (31).

Conclusion

This thorough analysis has highlighted the significant influence of photogrammetry in revolutionizing farming practices. Agriculture is poised to make dramatic advancements in resilience, sustainability and production by utilizing photogrammetric techniques. The potential for innovation in agricultural contexts is enormous. When using high-resolution pictures from various sensors and investigating cutting-edge methods like UAV-based photogrammetry. To fulfill changing agricultural requirements and environmental goals, these possibilities come with difficulties that call for ongoing research and innovation. However, photogrammetry's promise is still undeniable, providing agricultural stakeholders with hitherto unheard-of opportunities for ecological stewardship, resource management and precision farming. We are getting closer to a future where agricultural methods prioritize environmental awareness and resilience in the face of global difficulties, in addition to increasing efficiency, as we continue to push the limits of photogrammetric capabilities.

Future Perspectives

The future of photogrammetry in agriculture promises tremendous breakthroughs and closer integration with cutting -edge technology. The use of sophisticated sensors, such as LiDAR, thermal cameras and multispectral and hyperspectral imaging, to collect vast amounts of data on crops, soil and environmental conditions. It is one of the anticipated advancements. Large photogrammetric datasets will also probably be analyzed using machine learning and artificial intelligence techniques. This allows for yield prediction, automated crop disease diagnosis and real-time precision farming decision assistance. Photogrammetry will be essential in developing more robust, productive and sustainable agricultural methods as technology develops.

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Authors' contributions

VV prepared manuscript. MV, SN helped during collection of articles. RR, RKP participated in the sequence alignment and drafted the manuscript. BD participated in the sequence alignment. KM, AK quoted the references. All authors read and approved of the final manuscript.

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