ARCHIVES OF TRANSPORT
Volume 58, Issue 2, 2021

ISSN (print): *0866-9546*
e-ISSN (online): *2300-8830*
DOI: *10.5604/01.3001.0014.8796*

UNMANNED AERIAL VEHICLES SUPPORTING IMAGERY INTELLIGENCE USING THE STRUCTURED LIGHT TECHNOLOGY

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Abstract:

One of the possible tasks for unmanned aerial vehicles (UAVs) is field capturing of object images. The field capturing of object images (scenes) is possible owing to the UAV equipped with photographic cameras, TV cameras, infrared cameras or synthetic aperture radars (SAR). The result of the recognition is a metric mapping of space, i.e. 2D flat images. In order to increase the quality of image recognition, it is necessary to search for and develop stereoscopic visualization with the possibility of its mobile use. A pioneering approach presented in the research paper is using a UAV with an imagery intelligence system based on structured light technology for air reconnaissance of object over
a selected area or in a given direction in the field. The outcome of imagery intelligence is a three-dimensional (3D imaging) information on the geometry of an observed scene. The visualization with
a stereoscopic interface proposed in the work allows for a natural perception of the depth of the scene and mutual spatial relationships, as well as seeing which objects are closer and which are further. The essence of the article is to present the application of three-dimensional vision measurement technology on UAVs. The paper presents an analysis of the possibilities of using UAVs for image recognition and a method of image recognition based on the technology of structural lighting using the method of projection of Gray'a fringes and codes. The designed image recognition system based on the structural lighting technology is described. It also discusses task modules forming a measuring head, i.e., projection, detection and calculation modules, and the exchange of control or measurement data between imaging system components. It presents the results of tests on the possibility of rapidly acquiring images using a UAV. The test results and the analyses indicate that using a UAV with an imaging technology based on structural light can contribute to improving the abilities to detect, identify, locate and monitor objects at close range, within a selected direction outdoors or indoors.

Keywords: *aviation, unmanned aerial vehicle, reconnaissance, structured light*

To cite this article:

Ułanowicz, L., Sabak, R., 2021. Unmanned aerial vehicles supporting imagery intelligence using the structured light technology. Archives of Transport, 58(2), 35-45. DOI: https://doi.org/10.5604/01.3001.0014.8796

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1. Introduction

Wherever a person is confronted with a high threat, extreme mental burden, the required high concentration over a long period of time, heavy physical effort, unfavorable environment (e.g. operation in chemically, biologically or radioactively contaminated terrain), it seems appropriate to use an unmanned aerial vehicle (UAV). It allows you to reach and recognize places that are difficult to reach and dangerous to humans. UAV is a relatively cheap device, and its operator can be trained in a relatively short time (Hildmann and Kovacs 2019; Kampf et al. 2019; Łukasiewicz 2020; Zhou 2019). Intensification of work on unmanned aerial vehicles (hereinafter referred to as UAV) has been noted in recent years. Their primary field of application are military operations, however, it is possible to utilize this technology in other areas of life (Aguilar et al. 2017; Hildmann and Kovacs 2019; Kampf et al. 2019; Krassanakis 2018; Łukasiewicz 2020; Zhao 2018; Zhou 2019). In a review article by Kampf et al. 2019 compared the approach and rules for the use of civil and commercial UAVs in selected European countries. The authors emphasized the inconsistency of regulations within the European Economic Area regulating the use of UAVs in given countries. They discussed their own concept of using UAVs in biological protection of airports. The advantages and disadvantages of UAVs as devices supporting the physical protection system of critical infrastructure facilities on the example of a nuclear power plant are presented in (Łukasiewicz 2020). He showed that although the use of UAVs to increase the security level of critical infrastructure facilities has some limitations, the possibilities resulting from their usability are a decisive advantage of the need to implement UAV technology in security.

One of the possible tasks to be executed by UAVs is the acquisition of image and photogrammetric data in real-time, especially in terms of reconnaissance associated with widely understood security or conducted in difficult and dangerous field conditions, e.g., when evaluating damage and leaks at nuclear power plants or chemical plants. The field capturing of object images is possible owing to the UAV equipped with photographic cameras, TV cameras, infrared cameras or synthetic aperture radars (SAR) (Watts et al. 2012; Moranduzzo and Melgani 2014; Zhu et al. 2018; Ke et al. 2018). Image acquired from devices of this type is, however, devoid of stereoscopic perception, natural to humans (Moranduzzo and Melgani 2014; Zhu et al. 2018).

A kind of innovative challenge is the technology of image recognition in 3D format. Methods for constructing a scene in mobile applications and recognition of its elements are developed using numerous techniques and solutions (Adam et al. 2017; Bassan 2018; Liu et al. 2010; Salvi et al. 2010; Weingarten et al. 2004). These techniques involve determining numerous features based on the measurement data and, within the next step, an attempt to spatially correlate them, which enables constructing a 3D model. The basic features, which are taken into account and are based on determining the fundamental geometric primitives include lines, planes, circumferences, circles and areas of uniform colour (Jacyna et al. 2017). Each of these primitives can be determined using many numerical analysis techniques, such as the least squares method, division and merging method, linear regression or the Hough'a transform. In this case, the measurement outcome is a 3D information on the geometry of the observed scene. The main element, which enables identifying scenes and objects are visual sensors. Their fundamental types are based on the following measurement techniques (Gupta et al. 2013; Wang et al. 2010): Doppler's phenomenon, time of light measurement, sound time of flight measurement, laser phase-shift distance measurement, laser triangulation, stereoscopy, photogrammetry and structured light based on techniques with an accuracy to the nearest pixel, as well as sub-pixel techniques. These types of sensors are under constant development.

Recognition of the scale of destruction or damage to the structure in places difficult to reach and dangerous to humans requires the creation of images of objects in the field in close range. The most convenient tool enabling such recognition, due to the size of the measurement field and the accuracy of geometry, is a UAV equipped with a 3D scanner. A kind of innovative challenge is the adaptation of image recognition technology in 3D format to UAV applications. Currently, the recognition technology in the 3D format is characterized by oversized dimensions and power requirements, which limits its application to UAVs.

The essence of the article is to present a demonstrator of a measurement system based on structured lighting technology for three-dimensional imaging dedicated to use on UAVs. Due to the requirements for large measurement accuracy (0.1 mm) for the 3D image recognition technology, currently two methods can be utilized in such applications, namely, laser triangulation and structured light. Laser triangulation uses mobile mechanical elements for sweeping the laser beam across the field of view, with the elements possibly impacting the UAV hovering stability during the measurement. In the structured light method, the projector-camera system is composed of fixed elements and can be mounted very rigidly. The measurement is conducted in the structured light technology, using the fringe projection and Gray'a codes method. The structured light method involves a simultaneous projection of rasters from their system and their observation on the object through a CCD camera. Rasters falling on the measurement scene are deformed. The recorded deformation is the source of information on object shape. The measuring system consists of three elements of a visible range raster projector, CCD detector and a PC-based computer unit. A cloud of points (x, y and z), which illustrates the shape of the observed scene is the outcome of the measurement. The measurement data can then be subjected to the recognition and identification process based on objects already in the database or can be analysed metrically (measured distances, cross-sections, volumes, etc.). They can also be processed to a form of a textured triangle grid and visualized on graphics stations with a stereoscopic interface. Visualization with a stereoscopic interface enables perception of the scene depth natural to humans and seeing, which objects are closer, and which are farther.

The article presents the preliminary results of the study of the 3D UAV prototype.

2. Properties of unmanned aerial vehicles in terms of imagery intelligence

An unmanned aerial vehicle (UAV) is a mobile flying object, which does not require in-flight crew presence and is piloted remotely or follows an automatic flight route. A UAV is a structure consisting of an airframe, propulsion unit with its control and fuel system, UAV control and flight monitoring system, data transmission system and task-specific systems, e.g. imagery intelligence.

One of the most important UAV elements is the flight control and monitoring system (FCMS). An FCMS comprises an onboard control system (OCS) and a ground control system (GCS). The task of a FCMS OCS is the in-flight stabilization of a UAV and following its pre-set flight route, reading the flight parameters (aerodynamic from pressure sensors connected to a Pitot tube, spatial orientation from accelerometers and speed gyroscopes, as well as navigational parameters from a GPS satellite navigation receiver), filtering and processing of these signals in the microcomputer system, preparing the signal for transmission (via a radiomodem), and sending the data to a ground flight control and monitoring station (GFCMS). A FCMS OCS consists of an onboard radiomodem, autopilot, power and control signal distribution system, servomechanisms for steering surface tilting (in the roll, pitch and yawn channel) and the propulsion unit control system, remote control instrumentation receiver and transceiver antenna. The main element of the FCMS OCS is the autopilot with systems of spatial orientation, GPS navigation, mission control, automatic flight control in the pitch, yawn and roll channel, altitude and speed. Tasks implemented by an autopilot are:

– real-time determination of necessary accelerations and angular velocities, UAV spatial orientation angles, bearing, as well as flight altitude and speed,
– ensuring UAV stabilization (in the feedback loop), protecting against rapid disruptions like a blast of air or turbulence,
– acquiring data on UAV position, location of the destination and conversion of such data,
– maintaining a data link with the ground station in order to supervise UAV flight.

A ground flight control and monitoring station (GFCMS) is an integral part of a UAV, which is necessary to its operation. The tasks of a GFCMS are real-time UAV control during a mission task, receiving transmissions sent from onboard the UAV and decoding the data, graphical presentation of piloting and navigation parameters, and presenting a map depicting the planned and currently followed flight route. A ground flight control and monitoring station is comprised of GSS software (UAV control without direct eye contact between the operator and UAV – automatic flight mode), mapping screens, remote control instrumentation (control with direct eye contact between the operator and UAV – manual flight mode) and a radiomodem module with a transceiver antenna.

A UAV can be of airplane or helicopter design. A specific UAV design is selected depending on the mission to be executed. Airplane-like UAVs are characterized by long range and high operating ceiling. The reconnaissance zone achieved by an airplane-like UAV equipped with a digital camera, flying at an altitude of 200 m with a speed of 20 m/s (72 km/h) during a 30-minute flight (36 km covered) with a fixed observation angle of 45° is shown in Fig. 1. It is possible to take a maximum of 450 photographs in the course of an UAV flight at an altitude of 200 m, with a speed of 20 m/s (72 km/h) and a distance of 36 km. Object identification depends on image resolution, which is determined by the size of a single "pixel" (not closely correlated with lens focal length). General recognition, which enables verifying the presence of objects of characteristic shape, different in colour from the surroundings, requires image resolution of about 10% of their maximum linear dimension. Detailed recognition, which enables identifying the features of individual objects, requires image resolution not lower than ca. 4-5% of their largest linear dimension. Special airplane-like UAVs enable rapid acquisition of photographs in the visible light range, in natural colours, as well as infrared.

Helicopter UAVs exhibit shorter range and operating ceiling, but owing to their design, they enable vertical take-off and landing, as well as hovering over a structure. This enables long-term and accurate observation of selected ground objects at close range. Close range object image recognition can be achieved by helicopter UAVs with a system identifying and interpreting a so-called scene, i.e., volume, in which the measuring head is able to measure precise geometric parameters of the structures of objects therein.

A 3D visual measurement technology using the structured light method has been implemented in a single-rotor UAV with a tail rotor (Fig. 2) and a longitudinal twin-rotor UAV (Fig. 3). The measurement may involve various volumes, e.g., 1.5 m x 1.2 m x 1 m with an accuracy of 0.2 mm or 5 m x 4 m x 1.6 m with an accuracy of 0.6 mm.

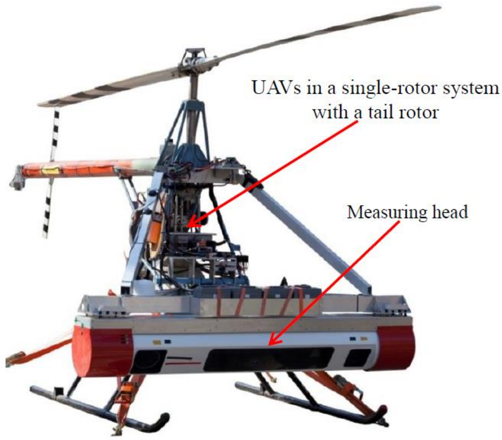


Fig. 2. UAVs in a single-rotor system with a tail rotor and a measuring head in the structured light technology

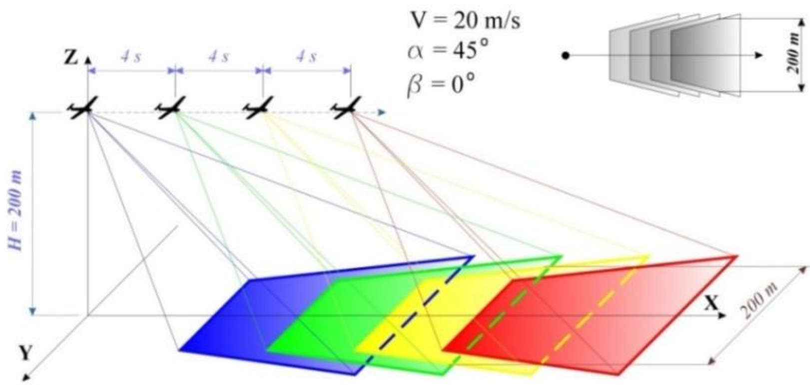


Fig. 1. Reconnaissance zone for fixed angle observation

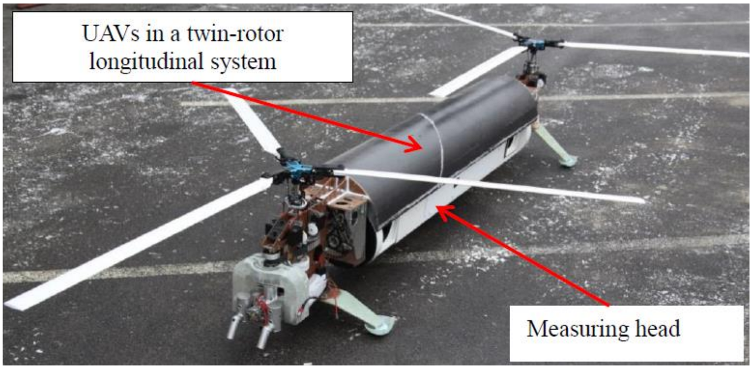


Fig. 3. UAVs in a longitudinal twin-rotor system with a measuring head in the structured light technology

3. Measurement of an object in the technology of structured lighting by the projection of Gray's fringes and codes

The structured lighting method is based on the simultaneous projection of rasters from the system and their observation on the object by a CCD camera. Rasters falling on the measurement stage deform on it. The recorded deformation is a source of information about the shape of the objects. The measurement system consists of three modules: a raster projector in the visible spectrum, a CCD detector and a computing unit. The result of the measurement is a point cloud (x, y, z) showing the shape of the observed scene. The time of a single measurement is about 1/30 second. After being sent to the computing unit, the measurement data is subject to the process of recognition and identification on the basis of the objects already in the database or can be analyzed metrically (measurements of distances, sections, volumes, etc.). They can also be processed into a textured triangle mesh and visualized on graphic stations with a 2D or stereoscopic interface.

Fig. 4 shows a diagram of the basic task modules making up a measuring head.

Dashed lines mark the control or measurement data exchange between the components, namely:

– the calculation module. Its task is to set the parameters of the structured light UAV measuring head subassemblies using a control module, receiving information sent from the distance measuring module regarding the distance to an observed object, downloading images recorded by the detection module and processing them in order to obtain a resultant cloud of 3D points. Furthermore, the calculation module is responsible for communication with the ground station and UAV autopilot;

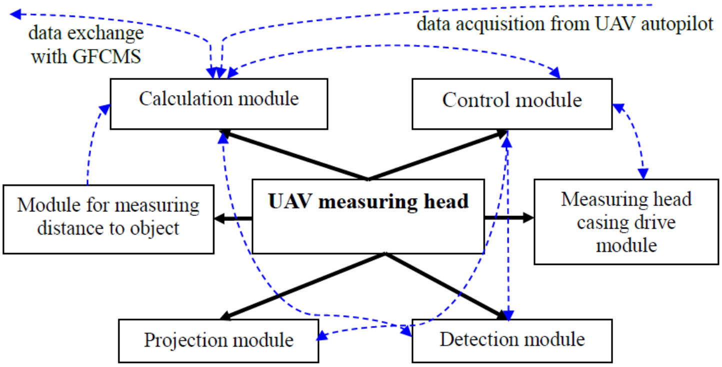


Fig. 4. Schematic diagram of the fundamental modules of the measuring head implemented onboard a UAV

- the control module. It is responsible for adjusting the detection and projection module parameters, and operating the drive module moving the measuring head. The control module is closely interconnected with the calculation module, constantly awaiting command from this module and sending own current parameters;
- the distance to object measuring module. It measures the distance between the measuring head and the observed object, and sends it to the calculation module;
- the measuring head drive module. It rotates the measuring head casing around its axis;
- the projection module. Its task is to project fringe images, which will be deformed on the surface of the measured element, and projecting raster images onto the measured object;
- the detection module. It acquires the images of the measured object illuminated with projected images by the projection module, and sends them to the calculation module.

Owing to the applied measurement method and the required measurement volumes, the projection and detection modules must be 1.5 m apart, and cannot change its position throughout the entire operation period, from the moment of calibrating the measurement system. In order to ensure appropriate positioning of the projection and detection modules relative to each other, they have been placed in a casing made of carbon fibre (see Fig. 2 and Fig. 3).
The principle of operation of the projection module is shown in Fig. 5. Engine 1 rotates a glass disc 2 with applied fringe patterns, which are illuminated by a flashgun 3 through a condenser 4. The image, with a fringe image matching the measuring phase is sent by the lens 5 towards the mirror 6, where it is reflected and exits the module, towards the measured object. In the case of a detector module (see Fig. 6), the structure of the mirror is the same as in the projection module.

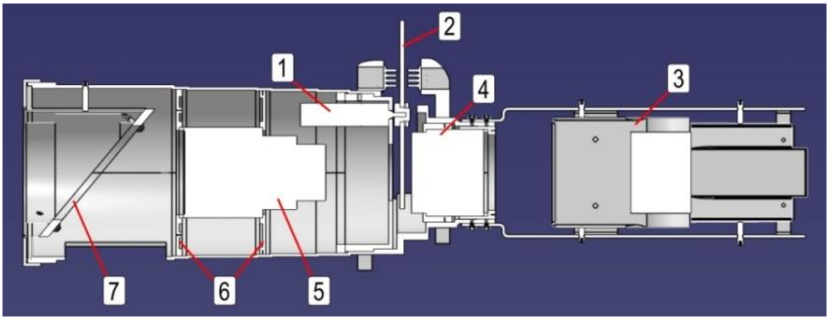


Fig. 5. Projection module of a structured light technology imaging system - 1) engine, 2) plate with fringe patterns, 3) flashgun, 4) condenser, 5) projection lens, 6) projection lens position adjusting rings, 7) mirror

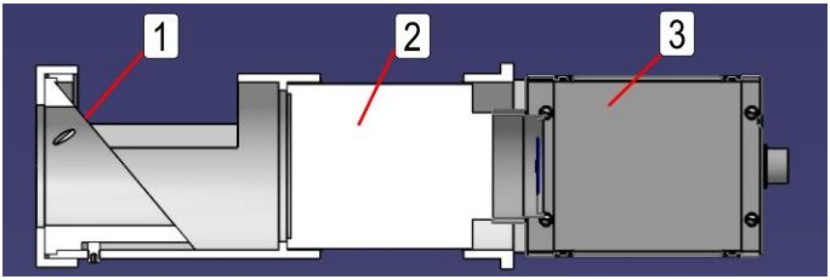


Fig. 6. Detection module of a structured light technology imaging system - (1) mirror, 2) lens, 3) camera

Diagram of a structured light technology imaging system calculation module is shown in Fig. 7. A computer performs advanced data processing and measurement process management tasks. It also acts as an element communicating with the UAV and GFCMS. The controller performs low-level processing, synchronization and communication with control elements. The head's rotation, enabling its parking on the UAV, is executed by software installed on the computer.

In order to provide effective writing and reading of database data and their explicit identification, the data stored in the database can be divided into two categories. The first one identifies measurement, reference and other data. Elements within this category have the format of text field descriptions. The second category includes binary data containing point clouds developed during the measurement, as well as reference data. Due to their size, the binary data are saved directly on the computer hard disc. The location of 3D data file and the ID data are saved in the database table fields. Database structure is shown in Fig. 8.

The 3D directional measurement system is attached to the UAV through a manipulator module. The manipulator module allows you to direct the measuring head itself in any direction, regardless of the orientation of the UAV itself, which is helpful in measuring the topography of engineering structures and building walls.

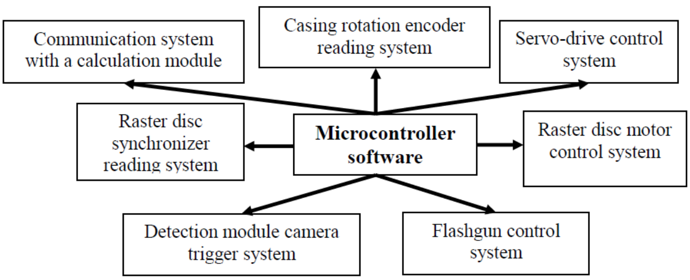


Fig. 7. Block diagram of a structured light technology imaging measuring head calculation module

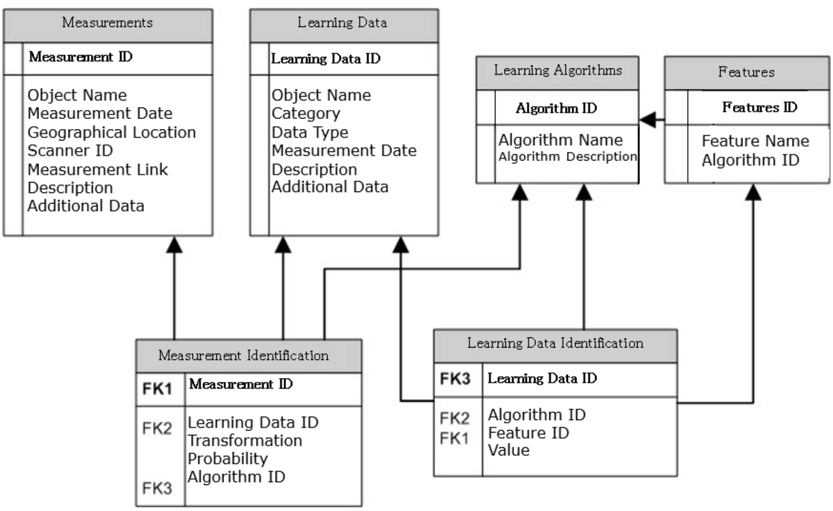


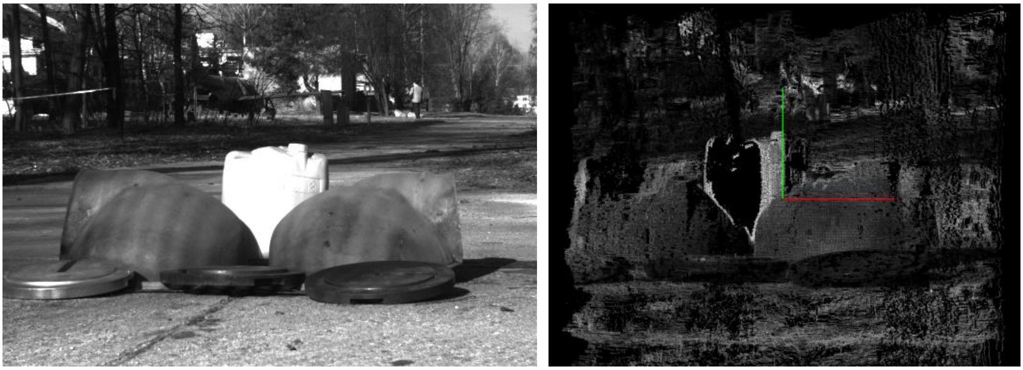
Fig. 8. 3D object database structure diagram

4. Results of tests involving UAV with an imagery intelligence measuring head using the structured light method

The research involved using UAVs with a single-rotor and a tail rotor (Fig. 2) and a measuring head with a 5 m x 4 m x 1.6 m measuring volume, which enables measuring from a distance of up to 20 m, with an accuracy of 0.6 mm. The improvised measurement scene is shown in Fig. 9 - the photo was taken with a camera.

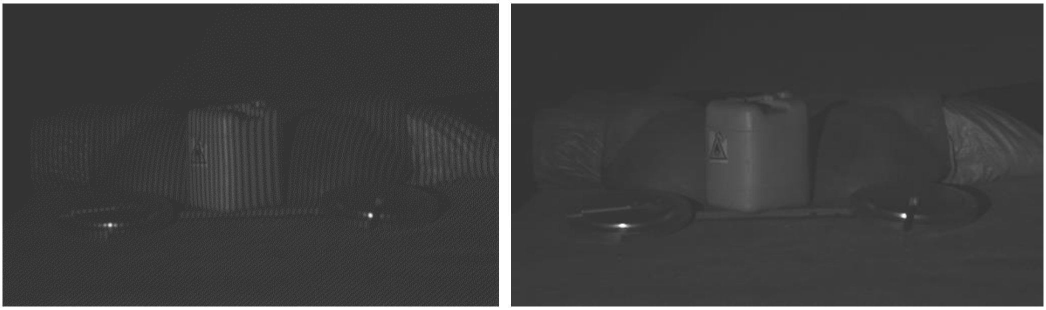
Fig. 9. Measured object fragment - photograph taken with a photo-camera

Flight tests were carried out in two stages. The first stage on a sunny day around 1pm and the second stage in the evening after sunset.
Fig. 10 shows the images recorded during one of the measurements taken during test flights carried out on a sunny day. Fig. 10a) shows the first of the Gray-framed images from the measurement sequence of the daytime tests. The stripes are barely visible on the laminate object and completely invisible on the yellow canister. Fig. 10b) shows a point cloud calculated from the recorded fringe images with such a low contrast. The view from the viewing angle of the measuring head detector seems quite correct at first glance. This is because the texture from the last recorded image is dumped onto the generated point cloud. However, in part of the picture, you can see points calculated chaotically in space. Such a shape of the determined point cloud indicates a very low contrast of the recorded fringe images. In this case, the calculation algorithm is not able to determine which pixel of the recorded image belongs to which sinusoidal fringe responsible for the proper representation of the shape of the tested surface. Measurements in such conditions (on a sunny day) are feasible, but they are characterized by low efficiency and a large number of errors generated by the measurement method due to the low contrast of fringe images.
Fig. 11 shows the images recorded during one of the measurements taken during test flights carried out in the evening hours after sunset. The images have been lightened by 10% for presentation in this article. Fig. 11a) shows a measurement frame with a sinusoidal fringed image and Fig. 11b) a measurement frame for texture recovery.
Fig. 12 shows the images showing the point cloud calculated on the basis of the acquired measurement sequence. The point cloud images presented in Fig. 12 have errors in the form of breakout and a large number of noise points. These errors come from a large difference in the position of the measurement objects in the detector's field of view in individual frames of the measurement sequence.



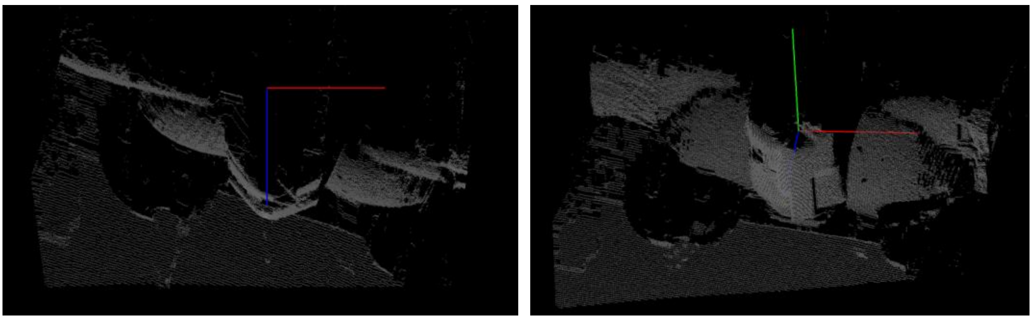
a) b)

Fig. 10. The images recorded during one of the measurements taken during test flights carried out on a sunny day



a) b)

Fig. 11. The images recorded during one of the measurements taken during test flights carried out in the evening hours after sunset



a) b)

Fig. 12. The images showing the point cloud calculated on the basis of the acquired measurement sequence

Fig. 13 shows the first (left) and last (right) frames of the measurement sequence overlapping each other. The difference in the vertical position of the elements observed during the in-flight measurements of the scene is marked with red sections. As can be easily seen, the position difference between these frames is considerable. Ideally, in order to achieve optimal mapping parameters of the surface measured by the 3D head, the objects on the individual frames of the measurement sequence should remain in the same place. The movement of objects in the detector's field of view during the recording of the measurement sequence was caused by difficulties in entering the hovering state of the UAV (assumed to carry out measurements with the 3D head). Fig. 14 shows the view of a point cloud composed of two directional clouds recorded during a stable UAV flight. The measurement is made correctly, it does not have significant punctures and shows the real appearance of the surface of the measured object.

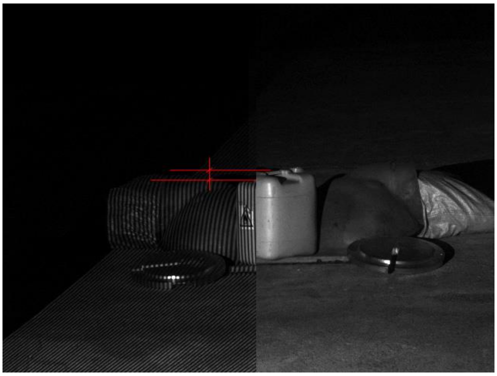


Fig. 13. Overlapping measurement sequence frames

5. Conclusions

3D imaging will increase and complete, compared to the current possibilities, the area of tasks in the field of reconnaissance and observation, especially in urbanized, wet and mountainous areas.

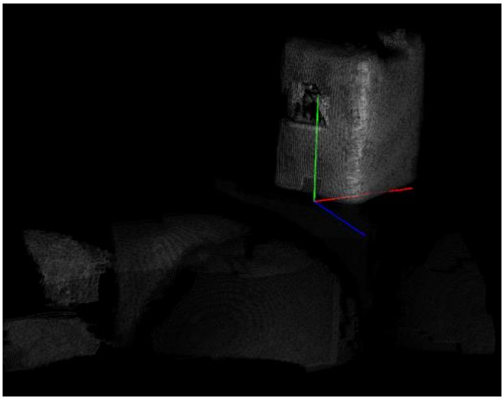


Fig. 14. The view of a point cloud composed of two directional clouds recorded during a stable UAV flight

Stable hovering of a UAV lasting 1-3 seconds is sufficient for the operator of the imagery intelligence system in the structured light technology to send a command to acquire a measurement sequence to the scanning device, and for the measuring head to execute this sequence. The mere time designing the fringe images and downloading them by the device detector is about 35 ms. During this time, the UAV should remain relatively stationary. The measuring heads applied in the course of helicopter UAVs enable measuring a scene (objects) in two volumes:

- 1.5 m x 1.2 m x 1 m with an accuracy of 0.2 mm, at a distance of 4 m from the measuring head,
- 5 m x 4 m x 1.6 m with an accuracy of 0.6 mm, at a distance of 20 m from the measuring head,

After being sent to a Ground Flight Control Station from onboard the UAV, the measurement data can then be subjected to the recognition and identification process based on objects already in the database or can be analysed metrically (measured distances, cross-sections, volumes, etc.). They can also be processed to a form of a textured triangle grid and visualized on graphics stations with a 2D or stereoscopic interface.

The prototype of the measuring head is under constant development due to its adaptation to UAV applications. Nevertheless, it can be concluded that even in the case of problems with the stable flight of the UAV, the scanning head is able to generate correct measurement data with the assumed accuracy. Obtaining correct measurement data depends on the measurement procedure, which should be called in the appropriate place of the measurement scene. The drawback of the developed technology is its sensitivity to sunlight on the measuring scene.

It is estimated that helicopter UAVs with a visual measuring head in the structured light technology can become important in terms of modern reconnaissance techniques, especially reconnaissance in difficult and hazardous terrain conditions, in terms of objects, which require precise identification and evaluation of, e.g., the technical condition, threat level, scale of destruction or damage, etc. Furthermore, UAVs of this type can be used for evaluating the damage and leaks within nuclear power plants or chemical plants, in places where access, even for land robots is hindered or impossible.

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