A local area UAS detection system from an elevated observation position

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ABSTRACT

We present a new approach to an optical UAS detection system that confirms several requirements specified by the authorities. Our UAS detection system consists of a ground unit and a convex mirror located in the air. The ground based unit contains high resolution camera system mounted on a pan tilt unit. Therefore, the lens of the camera system can be actively aligned to a convex mirror which is located in vertical distance over the ground unit on the lower side of a raised captive balloon. The focal length of the ground based lens, the altitude of the balloon and the curvature of the mirror define the field of view towards the ground. The recorded video streams are processed in a vision system using change detection and other algorithms to alert a UAS intrusion. We will outline the design parameters of the optical system, the requirements and the implementation of the mechanical system as well as the active alignment system and show first results of outdoor operation.

Keywords: detection, tracking, Unmanned Aerial System, counter UAS, UAV, balloon

1. INTRODUCTION

Major outdoor events such as election campaigns, sport events or conventions of political leaders are nowadays potentially threatened by unmanned aircraft systems (UAS). Right now a permanent or temporary protection of industrial facilities or public infrastructure (IT, water, gas, power) is absolutely advisable. In future this will be an increasing challenge. New types of low cost UAS systems with smart features like collision avoidance or autonomous fly modes using GNSS controlled way-points are available for everyone on the market. This could prove to be a challenge for evaluating the local safety and threat situation for law enforcement and emergency services for civil or military authorities. An UAS detection system as a part of a general situational awareness system can contribute to a safe event performance. It should be mobile, operational within a short time period and user friendly for the operators. Furthermore, it has to be accepted by the public and protected against external interference. Possible scenarios include flying objects approaching from outside of the field of view and also small and high speed UAS. Afterwards, it should be capable of determining the UAS position in real-time to initiate possible countermeasures and to document illegal action. Thereby, optical detection methods could be used also against autonomously flying UAS without any RF signal communication or emission.

Our approach takes advantage of an elevated observer position without most of the conventional limitations. Usually cameras or electro optical sensors are therefore mounted on a telescopic post. But the achievable height is always limited due to rigidity or weight restrictions. Additionally, vibrations are initiated caused by wind or motorized controls like pan tilt units. This yields to motion blur or image shaking. The image quality decreased and information about the target objects are harder to get. Another restriction could be the usable field of view of the cam system. Only wide field lenses provide a large scene on the cam focal plane array. But for the backwards direction you need at least one additional camera system.

In this paper we present the optical and mechanical setup of our system as well as overall system requirements and design considerations. The evaluation of our system under outdoor conditions is still under progress and will be presented in a follow on paper.

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2. SYSTEM REQUIREMENTS AND DESIGN CONSIDERATIONS

Our UAS detection system is split into a ground unit and a convexly curved mirror floating above it in the airspace. The ground based unit contains a high resolution camera mounted on a pan tilt unit. Therefore, the lens of the camera system can be actively aligned to a convex mirror which is located in vertical distance over the ground unit on the lower side of a raised captive balloon. The focal length of the ground based lens, the altitude of the balloon and the curvature of the mirror define the field of view towards the ground. Due to this new point of view, objects can also be detected behind the line-of-sight. UAS targets entering protected zones are not able to hide behind natural or artificial objects like trees or buildings. Within this field of view defined by a cone shape any UAS intrusion should trigger an alert. Only one single camera system is necessary to monitor the protected zone. Motion caused by crosswind of the folding mirror will also be compensated by the integrated active tracking system of the ground unit.

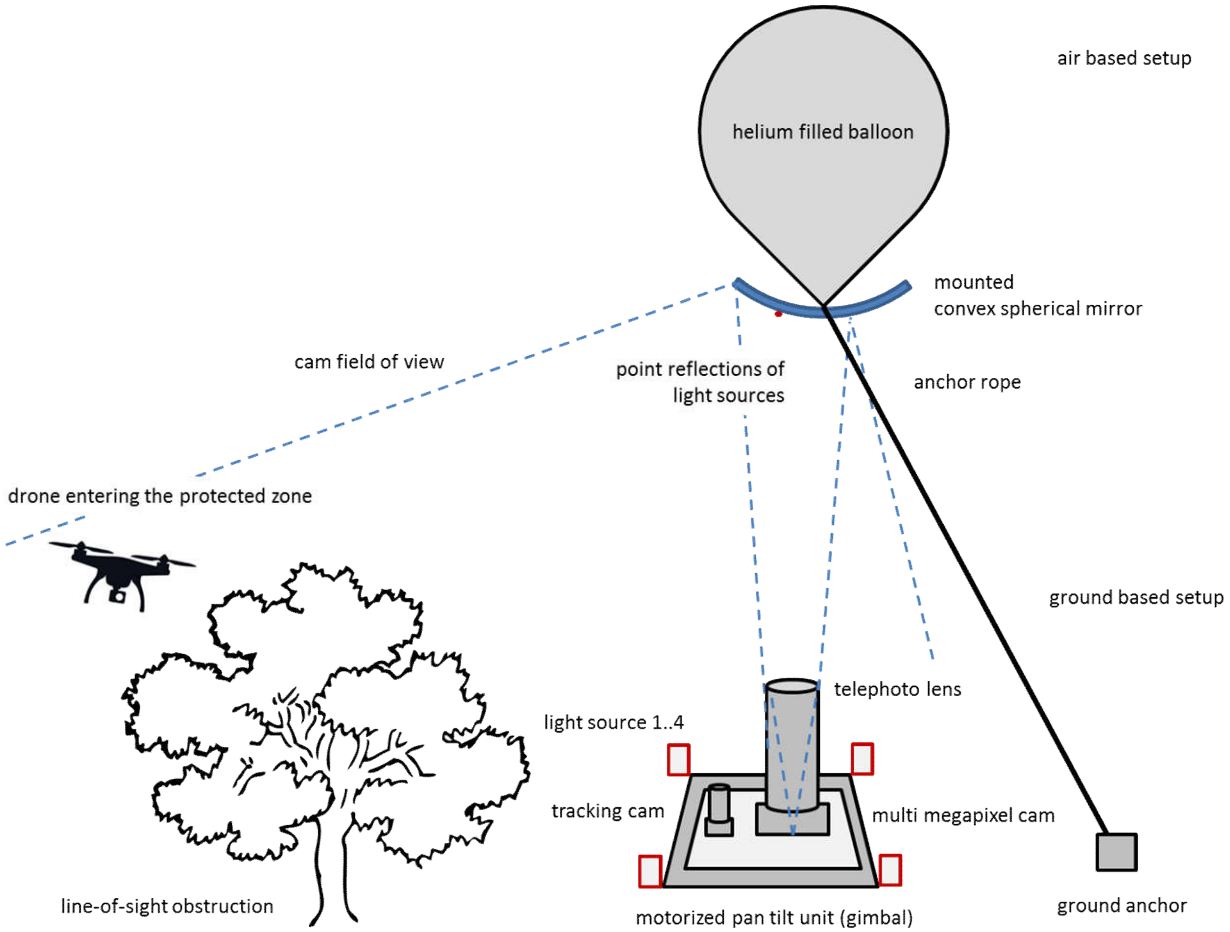

Figure 1. Arrangement of the air and ground unit setup that span a protected zone against incoming drone threats. The air based setup is fixed to the ground. The ground unit is aligned to the air based setup by an integrated tracking system.

The requirements coming from the user perspective complement technical specifications. Sometimes they even have opposed needs. Our approach satisfies many of these requirements.

Frequently changed sites of operations want for a mobile solution. The whole UAS detection system should be divided in single parts which can be handled by 1 or 2 persons. The time to come into operation should be short as possible. Depending on the mission or scenario only few minutes will be acceptable to start. The system should be ready for operation for at least 8 hours or better for a few days without any recharge or break. Financial cost should be acceptable. Especially a distributed approach, integrating many high-tech devices, could prevent a commercial success. Our balloon

produces low cost and the folding mirror is a part of a road traffic safety mirror. The balloon needs only 15 m³ helium to lift off in the air for a few days without reloading the helium. To operate a UAS detection system in public space, the system has to widely accept from visitors or citizens. In general a balloon looks friendly and is well accepted also by children. No camera observer system will be visible from the ground. Interference with other RF devices like mobile phones or other remote devices may be not expected due to the complete passive optical setup of the air spaced system. Custom jamming transmitters are not able to interrupt the operation. The ground based system contains all the high end optical devices and electronics at one point. So it will be easily to keep the more expensive part under surveillance to prevent external attacks or vandalism. Last but not least the processed data should be able to transfer to external tool to generate appropriate situation reports.

The operation of such a system in Germany is in general free of administrational permission up to an altitude of 30 m. Balloons operating at heights above 30 m have to be declared and registered by the local authorities. Therefore the operator has to comply with the requirements like valid aviation insurance and the permission from the owner to start from his ground. Due to data protection regulations (Germany: Federal Data Protection Act) and consultation right of the works council it has to be ensured that in all recorded and transferred images protected data like persons and license plates are not identifiable. Well known vision algorithms like face detection or number plate recognition are published in the literature [1] which will be used to filter the data stream to garble these objects before the operator has access to the video data. Beside, security authorities companies or private persons are also allowed to operate such a system in the public.

3. OPTICAL SETUP

The air based setup consists of a balloon and a fixed convex mirror orientated upside down. It turned out that the connection between mirror and balloon has to be close together to prevent generation of disturbing oscillations. Ten pick-up pads are available at the lower side of the balloon, which are tied together with self-made lightweight application points on the mirror frame.

Figure 2. First flight of the 3.5 m balloon filled with helium gas. The 1 m convex mirror is fixed upside down on the balloon to flip and expand the field of view of the operator perspective. One can see inside the mirror a section of the local test site.

3.1 Convex Folding Mirror

Different requirements of the applied mirror have to be considered. The maximum mirror mass should be < 5 kg to be able to raise the mirror with the balloon. A suitable diameter of the mirror is within the range of 60 – 100 cm. The optical shape of the mirror surface has to be convex and spherical. Distortions from the ideal shape should be minimized to achieve best imaging conditions.

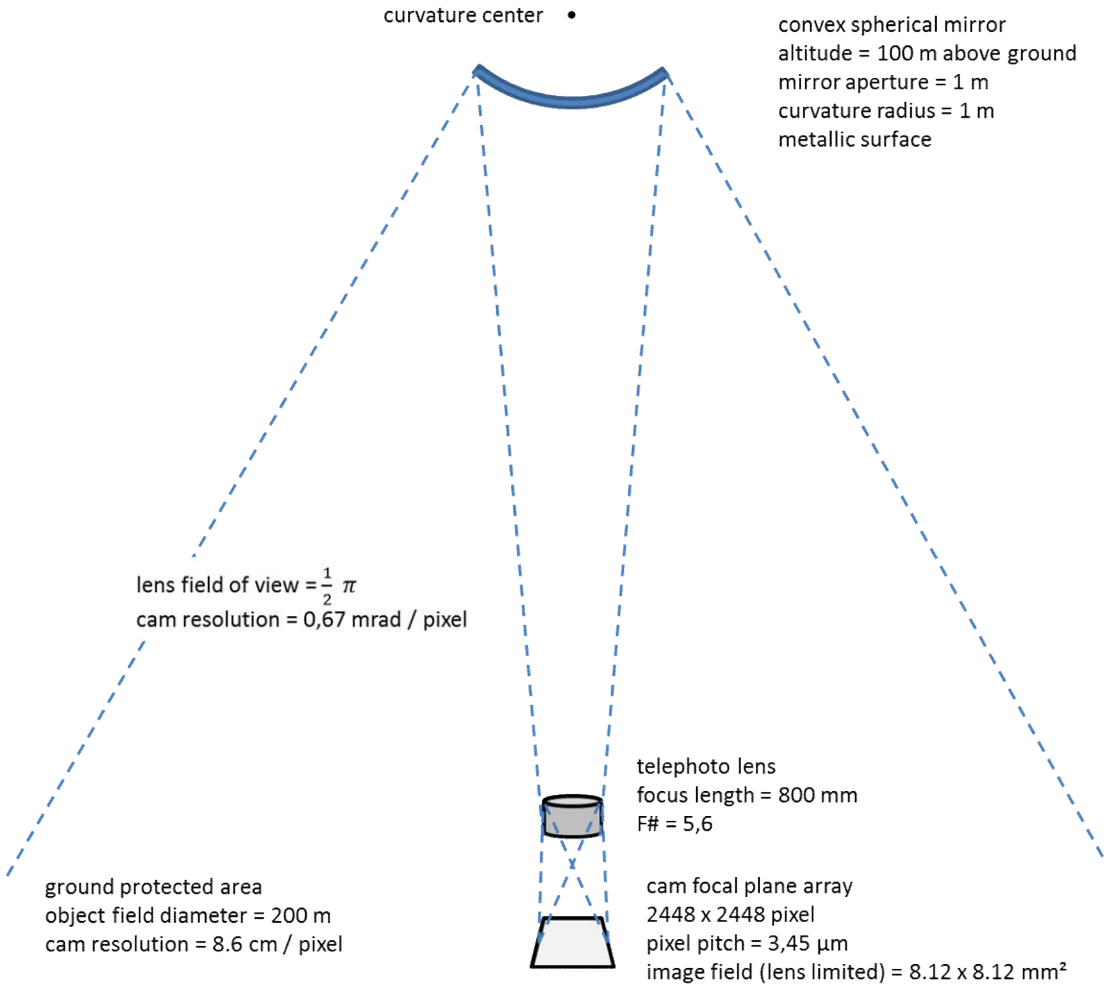

Figure 3. Optical setup of the ground based telephoto lens located in front of the cam focal plane array and the air spaced system with folding spherical mirror hover 100 m above by means of a captive balloon.

A large mirror aperture diameter and a small curvature radius will in general increase the field of view. But it is helpful to remember that the mirror aperture cannot be larger than two times the mirror curvature radius. Taking the weight of the mirror into account, which is limited due to the balloon lifting force, the folding mirror has to be lightweight. Such large mirrors are difficult, expensive and suffer from low optical surface quality. As optical distortions of the folding mirror cannot be avoided, image evaluation has to deal with distorted or sometimes blurred images. Therefore the video stream has to be post processed by algorithms to align the images using characteristically features inside each video frame. Wind can have negative impact on the position stability of the balloon and likewise on the folding mirror. This influence on the image quality can be compensated if the mirror can only rotate around its curvature center. From the point of the ground unit the surface doesn't change its local spherical shape. The curvature of the partially spherical mirror surface used for image formation will then be the same for each temporally rotation position. One result would be that the optical system appears more immune against external disturbance like crosswind.

3.2 Surveillance Camera System

The ground unit contains the UAS camera detection system mounted on a gimbal pan tilt unit. The UAS detection cam system consists of a tele zoom lens, a controller to drive focus and aperture as well as an industrial cam.

The off-the-shelf tele zoom lens is a conventional still imaging lens used widely for photography. Designed for 35 mm sensors measurements this lens confirms a minimum of distortions for small industrial focal plane arrays with a chip size below 1 inch. As a result of the low F-number of 5.6 the lens can be used also during low light conditions. The zoom function enables the adjustment of the cam field of view to fit the diameter of the folding mirror. The back focus length is a little shifted from the infinity point by -6.5 mm conforming imaging laws.

Typically, photographic lenses are equipped with motors to drive aperture and focus position. On the lens backside an EF mounted controller system provides a serial interface for communication. Using a TCP/IP port the user control and monitor the lens by serial commands.

The attached industrial cam includes a high resolution focal plane array to resolve the scene. A global shutter mechanism prevents motion blur. For high sensitivity, low noise and high dynamic range a CMOS FPA is recommended. A frequently used CMOS chip is the SONY IMX 250 a 2/3" format chip with 2448 x 2048 pixels and 3.45 µm pixel pitch. Up to 162 frames per second are available to capture also fast flying UAS objects.

Together with the folding mirror the complete system provides a field of view from the balloon position of nearly Pi/2. With an altitude of the balloon of 100 m the system achieves an angular resolution of 0.67 mrad/pixel. Within the observed protected zone on the ground this results in a resolution of 8.6 cm. Sufficient to detected also small micro UAS.

3.3 Tracking System

Due to the small field of view of the surveillance camera, it is important that the ground unit always tracks the spherical mirror on the balloon. Especially the weight of the megapixel camera for UAV detection and the frame of the motorized gimbal cause high inertial momentum. On the other side tracking has to be sufficiently fast, which results in difficult requirements for the motors and their controllers regarding the delay times.

To generate a measurement signal, an additional black and white (B/W) tracking camera with a 50 mm / F 1.4 lens is attached to the same gimbal. Furthermore, up to four very bright light sources are attached to the corners of the ground unit. Their light is reflected by the spherical mirror directly back to the tracking camera. This setup guarantees short exposure times, a simple image processing and therefore fast tracking. Figure 4 shows an image captured by the tracking camera. Due to the short exposure time of 1 ms the four bright light sources are easily identified.

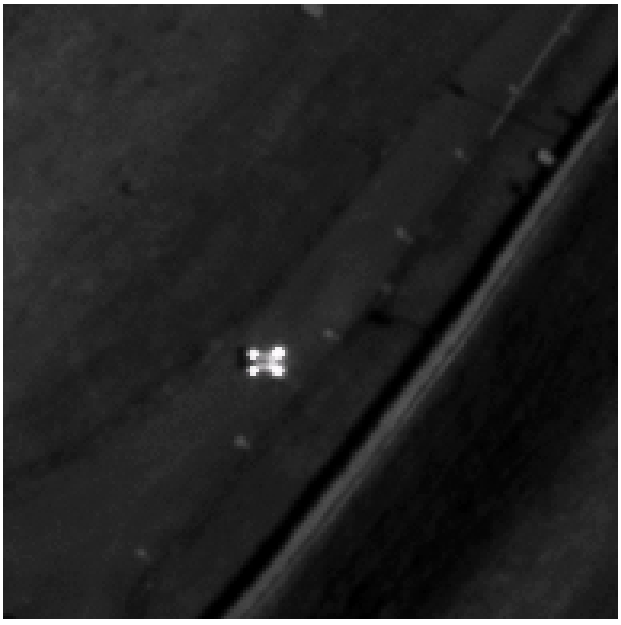

Figure 4. An image captured by the B/W tracking camera. Four bright light sources are located at the corners of the gimbal.

The tracking image processing can be explained in four steps. First, one field of interest (50 x 50 pix) is extracted around the preview detected light source position. Then the steps thresholding and binarization suppress all image information that doesn't belong to bright light sources. Finally the four centroids are calculated. These functions are not computationally expensive. Thus, the image processing takes less than 100 µs of time on a modern personal computer.

The command values for each axis are then calculated by PID controllers. The resulting target speeds are transferred via USB cable to the motor controllers of the gimbal. The whole control loop has an update frequency of 200 Hz.

For the functionality of this tracking algorithm only one bright light source is necessary. More light sources and the specific geometry are used to distinguish them from other bright light sources like sun glints.

4. MECHANICAL SETUP

4.1 Gimbal

We designed a motorized gimbal which carries both camera payloads. The main task of the gimbal is to steer and point the cameras in the direction of the spherical mirror, which is mounted on the lower side of the balloon. This gimbal has to fulfill several specifications. First, it has to be easy to transport. So we add wheels and we limit the external dimension to 70 cm x 70 cm. Thus, the gimbal fits through standard doors. Then the gimbal has to follow the balloon even when if wind is blowing the balloon to the side. Therefore, our gimbal offers a free swiveling range of ± 40°. In this full range the motors shouldn't be overloaded. Thus we fixed the large 800 mm lens in a way that the center of gravity is a bit below the pivot point. Additional devices like the tracking camera, the angular encoder are compensated with small counterweights.

Figure 5. Mobile ground based setup consists of a motorized gimbal used as a pan tilt unit. Surveillance camera is located within the pivot point of the gimbal. Lights on the corner are required for tracking the folding mirror. Safety issues like gear caps or an emergency stop are implemented.

It is a challenge to find small and cost-efficient servomotors off-the-shelf with sufficient angle accuracy and torque. That is why we opted for an in-house production. We used motors and gears of two high quality RC servomotors. Without the integrated servo controllers they are not limited to a swiveling range of 180°. The RC servomotors provide a torque of 3.5 Nm. This torque is transmitted to the axes via a toothed belt and two wheels with 20 and 40 teeth. This leads to an additional transmission ratio of 1:2 and doubles the torque at the axes. The number of teeth can easily be changed to further increase the torque if it is necessary.

We measure the actual angle of the axes with two 16 bit encoders. They provide a standard SSI interface and can easily be read out. The motor controller is implemented on an Arduino Mega 2560 board. For the motors we added a 4 A motor shield and for the encoders two RS422 shields. The control loop is implemented as a speed controller with an update frequency of 1 kHz. The control signals (target speeds) are transmitted via USB from the higher-level control loop.

4.2 Balloon

Holding the balloon above the ground unit three ropes are connected to anchors on the ground. Potentially, wind can push the balloon out of its steady state, but the variability of motion is limited by the anchor system. It has to be in the responsibility of the operator to avoid collision with electrical power supply lines or other objects around the system for save operations. In general the system should not be used unattended.

The balloon with a diameter of 3.5 m is made of PVC. Filled with maximum 23 m³ helium gas the balloon can fly in the air for many days. The carrying capacity of such a balloon is about 10 kg. Balloon operations with wind velocities up to 20 km/h are applicable. High-strength Dyneema SK78 nylon ropes with 1 mm diameter are used to hold the balloon in position. The rope material is extreme tear-resistant, qualified for low strain (< 1%) and weather proof. An anchor rope of 100 m has only a weight of 90 gr.

5. IMAGE PROCESSING

Most small UAS have a very distinctive shape when viewed from above. Furthermore the visible area is larger than from a front view. We can utilize this to detect UAS in the image stream of the camera by using image processing. To do this, the images have to be preprocessed.

In spite of the tracking, there is still some movement in subsequent images of the camera caused by wind. This results in a wiggly video stream. Therefore it is necessary to stabilize the images first. We use a hotspot detector on the bright light sources on the ground unit, similar to the tracking. The resulting images are aligned so that the ground based camera is in the center of the frame.

Due to distortions of the spherical shape of the convex mirror there are slight movements in different regions of the image that are not caused by a moving object. Thus, a simple object detection by calculating the difference of subsequent frames is not constructive. We use a background subtraction algorithm based on a Gaussian mixture model [2] to detect moving objects.

Further work will be necessary to determine whether the detected moving object is a UAV or not. For that purpose we are going to train a convolutional neural network.

6. FIRST RESULTS

A first attempt was done on the test range at DLR Lampoldshausen. The balloon was filled with helium and raised up to 50 m over ground. Three ropes are connected to anchors to hold the balloon above the ground. The tracking system was activated to align the ground system automatically to the folding mirror. The ground based camera system was started to record video streams of the surrounding area. One or two test drones were started to enter the protected zone.

Potentially, crossing wind pushes the balloon out of its steady state, but the variability of motion is still limited by the anchor system. However the balloon requires more or less windless condition. Wind speed of more than 1- 2 Bft (3 m/s) can drift the passive balloon outside its working zone. It has to be in the responsibility of the operator to avoid collision with electrical power supply lines or other objects around the system.

As a result of this first attempts investigations of the image quality indicates that the folding mirror produces local distortions. After a replacement of the folding mirror by a stainless steel model (r = 2.2 m, dia = 0.6 m) the image quality could be essentially improved. But it has to be taken into account that the parameters of the designed setup were

changed. Spatial resolution and diameter on the ground of the protected zone are decreased. The evaluation of the setup and the outdoor experiments are still under progress and will be presented in a follow on paper.

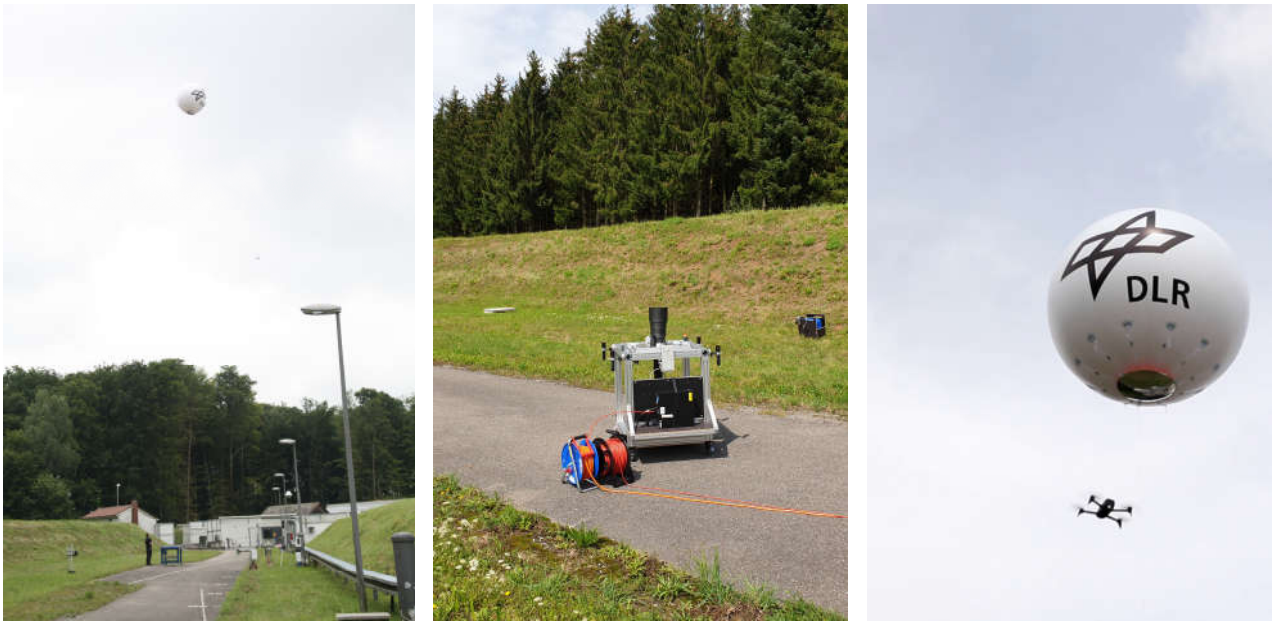

Figure 6. Local test area at DLR Lampoldshausen site. Balloon was raised up to 50 m over ground. UAS detection system was remotely controlled over Ethernet. The tracking system was activated to point the cameras to the folding mirror. Test drones are in the air to act for typical threats.

ACKNOWLEDGMENT

The authors want to thank the joint board of DLR for funding the project within the DLR internal contest “Wettbewerb der Visionen” 2018 – 2019.

REFERENCES

[1] Escriva, D. M. and Shilkrot, Roy, [Mastering OpenCV 4 - Third Edition], Packt Publishing, ISBN: 9781789533576, (2018).
[2] Zivkovic, Z. and van der Heijden, F., "Efficient adaptive density estimation per image pixel for the task of background subtraction," Pattern Recognition Letters 27(7), 773-780 (2006).