Real-time 3D inspection of large civil structures using a stereoscopic camera system equipped UAV

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Abstract

REALTIME3D is an innovative Mixed-Reality (MR) photogrammetry system that integrates photogrammetry, UAV technology, and VR/AR solutions to enable real-time 3D infrastructure inspection. By combining these technologies, the system allows users to remotely access, visualize, and measure 3D stereoscopic models in real time. An operator on-site pilots a UAV equipped with the stereo cameras, while experts, utilizing VR headsets, can observe and analyze the object of interest from remote locations. This approach enhances cost efficiency and safety during inspections of large-scale, critical structures. The paper introduces the first prototype of the system, detailing its hardware and software components.

1. Introduction

During both the analogue and analytical photogrammetry, the photographic cameras were used as the sole data source, whereas processing was done by use of a great variety of devices (analogue stereo instruments of many types, mono- and stereo-comparators, rectifiers, triangulators, orthophoto projectors, and analytical plotters). Later, the situation was completely reversed in the digital photogrammetry, which is still dominating type in the industry and academia. For data acquisition, a great number of different sensors (CCD and CMOS cameras, linear array cameras of various types, digital panoramic cameras, laser scanners, structured-light systems, MMS, microwave and ultrasound sensors, X-ray devices and electronic imaging devices) have been used, whereas data processing has been done solely on the workstations/servers with the specialized software. A1l photogrammetric and remote sensing functions that had been executed in the past on different instruments can now be integrated under a single software system (Baltsavias and Gruen, 2003; Gruen, 2008).

We observe the future trend where the data acquisition sensors and the processing devices tend to be unified. We envisage the next era, so called the real-time photogrammetry where the on-line processing is done either on the PCs next to the sensor on-board the platform or on the clouds. Since the computation power and data storage is moved out-of-office, the workstations are replaced by the simple terminals and monitors, VR headsets and AR googles.

REALTIME3D represents one of the pioneering prototypes in this emerging trend (REALTIME3D, 2024). This research initiative is co-funded by the national funding agencies of the EUREKA member countries—Switzerland, Türkiye, and Germany—through the EUROSTARS program and the European Union's Horizon 2020 Framework Programme, covering the period from 2022 to 2024. The project aims to develop a live-streaming, multi-user Mixed Reality (MR) photogrammetry system, featuring 3D stereoscopic visualization and a stereo-camera-equipped UAV, designed for a wide range of inspection tasks.

1.1 Objectives

Infrastructure systems, such as power grids, transportation networks, and communication systems, face ongoing challenges from natural and human-induced pressures, making their monitoring essential. Due to the complexity and high costs involved in their construction, regular maintenance and inspections are indispensable. Unanticipated damage can result in significant economic losses and potentially catastrophic consequences. As a result, the consistent monitoring of structures like bridges, viaducts, dams, and towers is critical for ensuring public safety and facilitating their rehabilitation.

Safeguarding critical infrastructure is crucial for national security and the well-being of citizens. Recognizing this, the European Commission established the European Programme for Critical Infrastructure Protection (EPCIP) to mitigate the vulnerabilities of such systems. This initiative comprises a set of measures aimed at strengthening the protection of critical infrastructure across all Member States and key economic sectors in Europe.

Unmanned Aerial Vehicles (UAVs) has changed not only the user requirements in industry but also the research trends in academia due to their flexibility, portability and affordability features (Colomina and Molina, 2014; Noor et al., 2018; Nex et al., 2022). UAV, UAS, RPAS are the terms which are confused occasionally. The terminology has been studied by Granshaw (2018). UAV photogrammetry has potential to offer high accuracy results in comparison to the conventional digital airborne photogrammetry (Forlani et al., 2018).

UAVs have been used for monitoring historic structures (Germanese et al., 2018), bridge inspection (Zhong et al., 2018;

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Liu et al., 2019; Yamane et al., 2023), crack detection (Meng et al., 2022), power line inspection (Li et al., 2022), energy infrastructure damage assessment (Bowman et al., 2023), open pit mine monitoring (Cao et al., 2023) and many other inspection and monitoring applications. The images are acquired in a strip or block formation with certain forward and side overlap ratios, and used in a subsequent post-processing step in order to achieve 3D information.

REALTIME3D was initiated as an international research project (https://rtime3d.com) with the objective of designing and developing live-streaming, multi-user, Mixed Reality (MR) photogrammetry software featuring 3D stereoscopic visualization for various inspection applications. This effort included the integration of a stereo camera rig as the image acquisition system mounted on an uncrewed aerial vehicle (UAV or 'drone') (Figure 1).

The stereo base length adheres to photogrammetric base-to-height ratio principles, enabling real-time 3D stereoscopic viewing and measurement. This is achieved through the combined use of an onboard PC, a 4G/5G modem, and cloud computing.

Figure 1: UAV used in the REALTIME3D system, equipped with stereo cameras.

The UAV system is operated on-site by an operator, while experts and engineers conduct inspections remotely using virtual reality (VR) headsets. The project's MR photogrammetry software enables multiple users from different locations to connect to the system and visualize the object of interest in a 3D stereoscopic view, complete with photogrammetric measurement capabilities. REALTIME3D is unique in that it integrates data acquisition and photogrammetric image processing into a unified workflow, performed entirely in real time. Photogrammetric outputs are interactively and simultaneously shared among multiple users, regardless of their geographical locations. Furthermore, REALTIME3D delivers an exceptionally rich visualization experience, often surpassing the level of detail and immersion achievable on-site.

Section 2 introduces the REALTIME3D system with its individual components in terms of software and hardware. Section 3 gives the results of the photogrammetric camera calibration work. Section 4 gives conclusions.

2. System Components

The REALTIME3D system consists primarily of a UAV equipped with stereo cameras and an MR-based photogrammetry software suite, designed for real-time inspection of critical infrastructure (Figure 2). The hardware and software components are seamlessly integrated into a unified pipeline, offering capabilities for real-time image acquisition and photogrammetric processing. The system includes the following components:

1. UAV carrying stereo cameras and on-board software
2. Mixed-reality photogrammetry application running on VR headsets
3. The backend and the web application running on the cloud servers.

Asynchronous monoscopic cameras (photo & video) are widely used onboard UAVs. However, the use of the simultaneous stereoscopic camera systems in the geospatial market is new and uncommon, and the few that are available are limited to academic purposes.

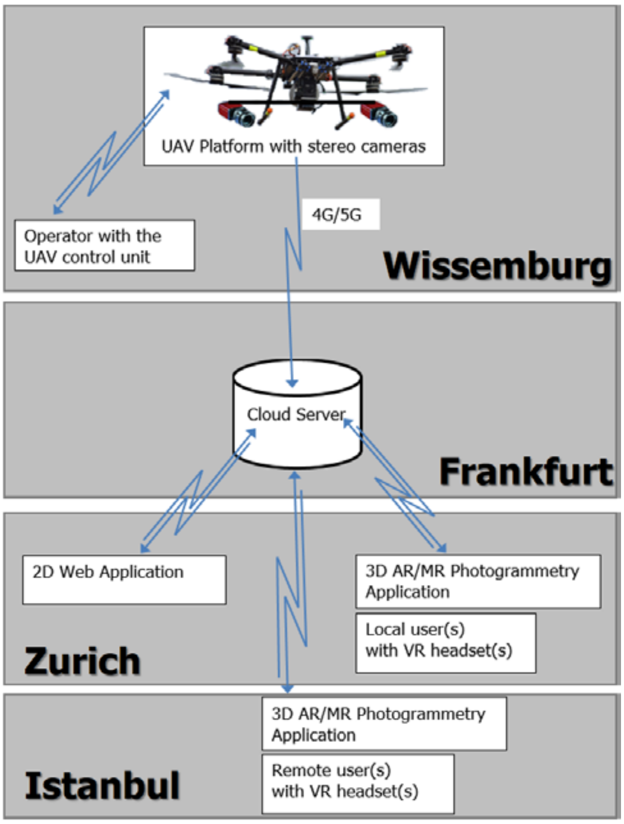
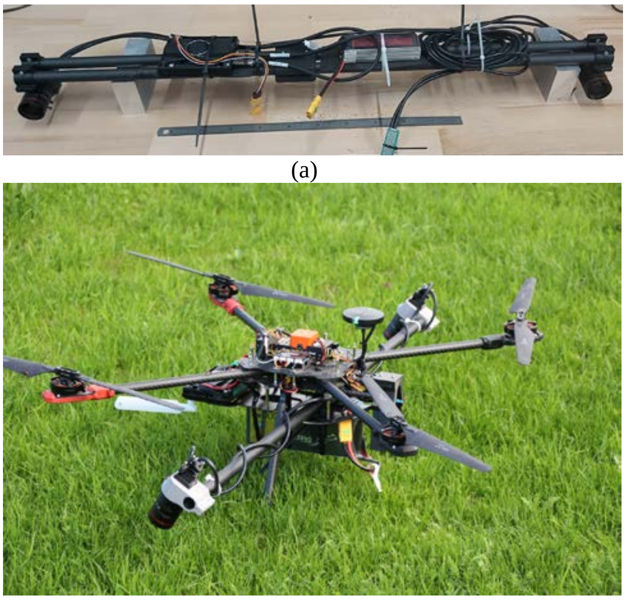


Figure 2: Architecture of the REALTIME3D system. Each grey rectangle represents a potential location in the world.

2.1 UAV carrying stereo camera and onboard software

The GGS AeroSpector (AS) 800 UAV is used as the aerial platform for the project. It has a good effective flight time, a good cost/performance ratio, and standard components in the case of repairs, replacements and modifications (Figure 3).


(a)

(b)

Figure 3: (a) Stereo-camera rig configuration. (b) GGS AeroSpector 800 UAV with the mounted stereo-camera rig.

The AS-800 features a foldable carbon quadcopter frame, capable of carrying payloads of up to 2 kg. It is a fully assembled, ready-to-fly (RTF) drone equipped with Herelink remote control. The AS-800 has a motor-to-motor diameter of 800 mm. Without a payload, it achieves a flight time of approximately 70 minutes, while flight durations are reduced to about 52 minutes with a 500 g payload, 45 minutes with a 1,000 g payload, and 32 minutes with a 2,000 g payload. The drone's base weight, including all electronics, is just 1,800 g. With a 1,000 g payload and a 17,000 mAh GensAce battery, the total take-off weight remains under 4.5 kg.

The system utilizes two Alvium cameras with a high-resolution image format of 20 MP. These cameras are Allied Vision Alvium 1800 U-2040c models, featuring a USB 3.1 interface, a C-Mount lens connector, and a CMOS sensor with 4.512 x 4.512 pixels at a 2.74 µm pixel size. Designed for industrial applications, these cameras are lightweight, energy-efficient, and equipped with highly durable sensors. Both cameras are paired with 16 mm high-resolution lenses from the same manufacturer.

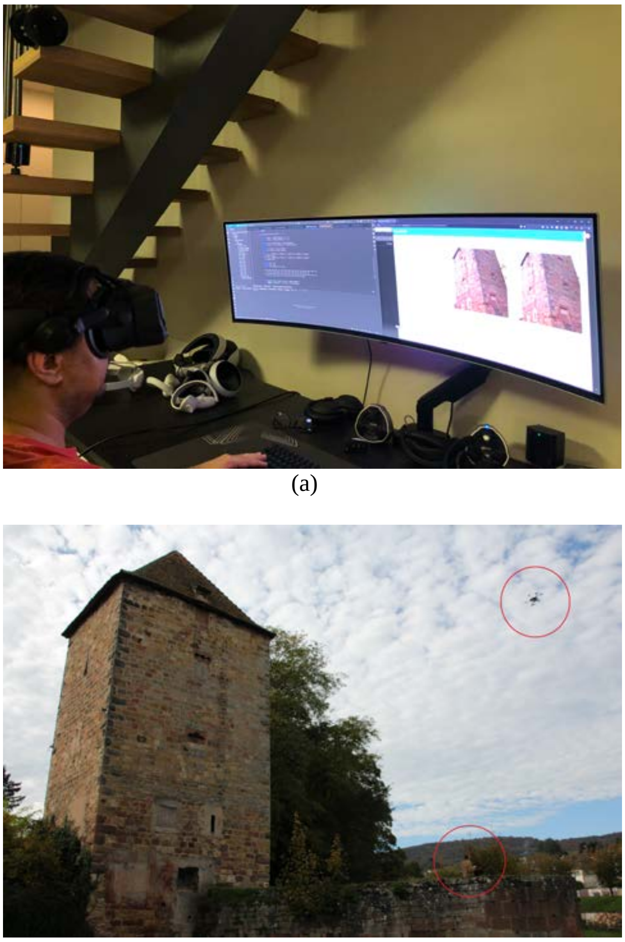
Mounted on either end of a 1-meter carbon tray (stereo rig), the cameras are tilted approximately 5 degrees to achieve a convergent imaging geometry. They are connected to an onboard PC (Latte Panda 3D), which handles image pre-processing and data transfer. The cameras are powered via a USB-3 interface using Power over Ethernet (PoE) and controlled through the Vimba SDK software development kit. A separate port links a camera trigger interface to the UAV controller. Additionally, GPS-RTK geotags and inertial measurement unit (IMU) data can be streamed in real time along with the images, if needed.

2.2 Mixed-reality photogrammetry software running on VR headsets

Calibration of the stereo cameras and their relative orientation is done using Australis photogrammetry software with the calibration targets. Calibration information is passed to the backend software on the cloud server where distortion-free normalized image pairs are generated. These images are sent to the MR photogrammetry application (Figure 4) for stereoscopic view generation. Users from multiple locations can access these stereo pairs with their VR headsets and interactively inspect the real-world objects.

Figure 5 shows a typical scenario in which the user has the real-time access to the 3D stereoscopic model of the area-of-interest meanwhile the UAV is run on-site by an operator.

Figure 4: Graphical User Interface (GUI) of the REALTIME3D MR photogrammetry application.


(a)

(b)

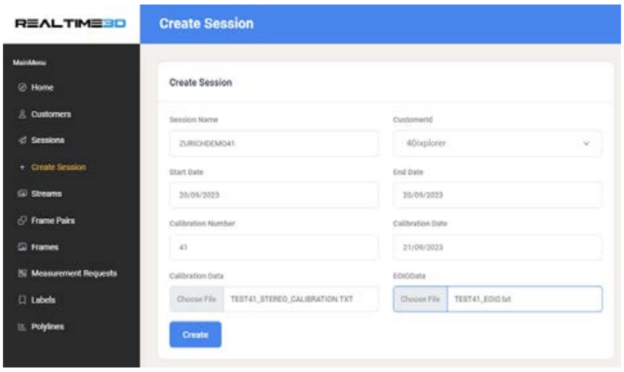
Figure 5: (a) Using a VR headset to interact with the REALTIME3D MR photogrammetry software. (b) Simultaneous stereoscopic image capture by the UAV at the site.

Developed using the Unity 3D engine, the MR photogrammetry software visualizes 3D stereoscopic models with capabilities for labeling, annotating, measuring, and vectorizing real-world objects in detail. A native 3D graphical user interface (GUI) optimized for VR is implemented to retrieve data from the backend and present it to users. Instead of traditional cartographic abstractions such as 2D maps or static 3D models, the software prioritizes augmented stereoscopic models as the primary format for storage and retrieval within the database.

2.3 2D Web application

The Web application (Figure 6) has the following functionalities:
(1) Application for administrative settings, data visualisation and auditing.
(2) Customers, sessions, calibration data operations.
(3) View sessions, streams, frames and stereo pairs, download images and other related data.

The web application allows for the visualization and partial editing of data collected by all system components. Serving as the central hub of the application pipeline, the cloud-based backend facilitates seamless integration. Users without access to a VR headset can still utilize the software through the web application, which provides measurement and annotation functionalities on 2D images.



Create Session

Create Session

Session Name: ZURICHDEMO41
CustomerId: 4Dixplorer
Start Date: 20/09/2023
End Date: 20/09/2023
Calibration Number: 41
Calibration Date: 21/09/2023
Calibration Data: TEST41_STEREO_CALIBRATION.TXT
EOIOData: TEST41_EOIO.txt

Figure 6: Overview of the REALTIME3D web application interface.

3. Camera Calibration and Image Normalization

3.1 Camera calibration

The stereo cameras onboard the UAV are to be used for 3D stereoscopic vision. Their calibration at beforehand is a necessity. A calibration flight for the photogrammetric camera calibration is flown before starting every new project.

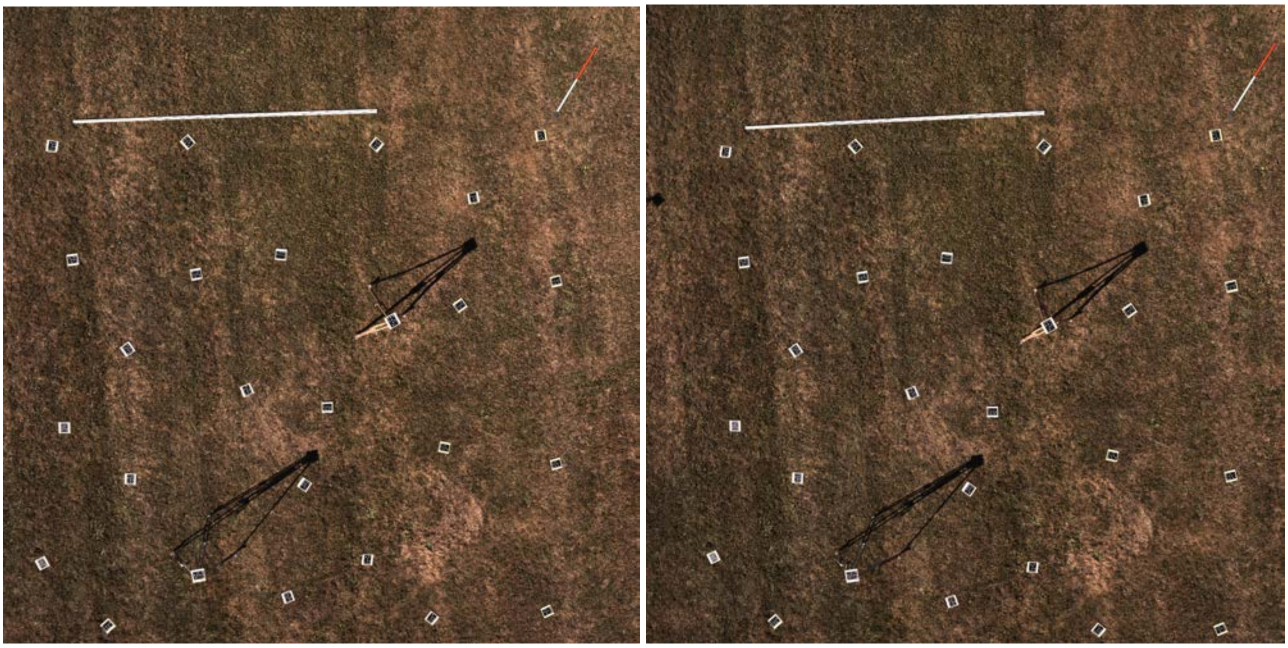

(a) (b)

Figure 7: Synchronized stereo pair: (a) Left camera image, (b) Right camera image captured in nadir view.

One of these calibration flights was done over a football field in Wissembourg (France) on 20.09.2023. Two different camera viewing modes were used in order to make the network geometry stronger. 20 stereo image pairs were acquired in the nadir view and 20 pairs in the oblique view (Figure 7).

The average flight height is around 8 to 10 meters. The coded targets of the Australis photogrammetry software were used for automatic point measurement (Figure 8).

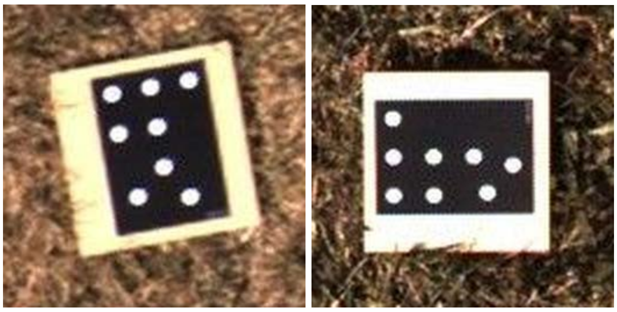


Figure 8: Calibration targets used with Australis software.

Australis photogrammetry software was used for the self-calibrating bundle adjustment (Australis, 2024). Estimated accuracy of 3D point coordinates were computed as:

X: ± 0.12 mm, or 1:104900
Y: ± 0.28 mm, or 1:42600 (height direction)
Z: ± 0.08 mm, or 1:155200

Overall is ± 0.18 mm, or 1:66300.

The interior orientation parameters and the lens distortion parameters of both of the Left and Right cameras were simultaneously computed. Moreover, the dependent relative orientation parameters between the Left and Right camera were computed (Table 1).

	Omega (grad)	Phi (grad)	Kappa (grad)	dX (mm)	dY (mm)	dZ (mm)
Averg.	0.2015	6.7457	0.5955	931.95	11.93	-60.55
Std. Dev.	0.0106	0.0265	0.0893	0.41	0.63	0.62

Table 1. The dependent relative orientation parameters of the Right camera with respect to the Left camera as origin.

3.2 Image normalization

Image normalization is required for the 3D stereoscopic vision. It is a resampling processing the Left and Right images into a new state where the y-parallax is eliminated (Cho et al., 1992; Anh, 2009; Kim and Kim, 2016; Tjahjadi and Handoko, 2020).

Figure 9 shows two normalized images, which have the common rotation angles (omega, phi and kappa) and the epipolar line in the left and the right images have the same y coordinates. Thus, the y-parallax has been eliminated. The normalized images must be parallel to the airbase and must have the same focal length. Having chosen a focal length, there is still an infinite number of possible normal image positions (by rotating the images around the airbase).

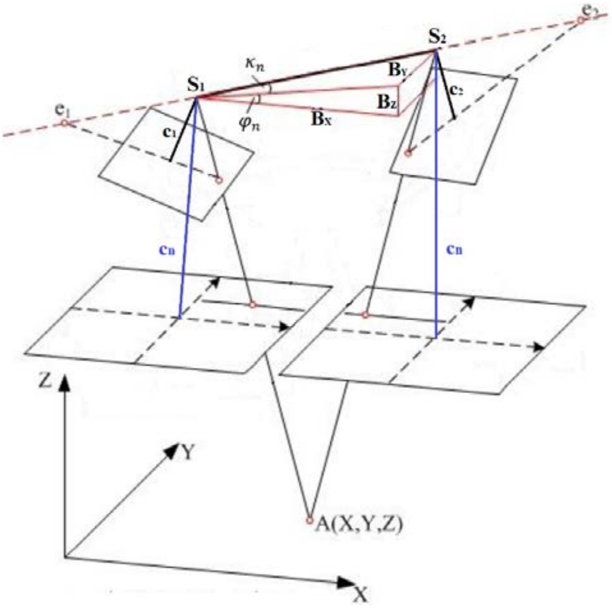


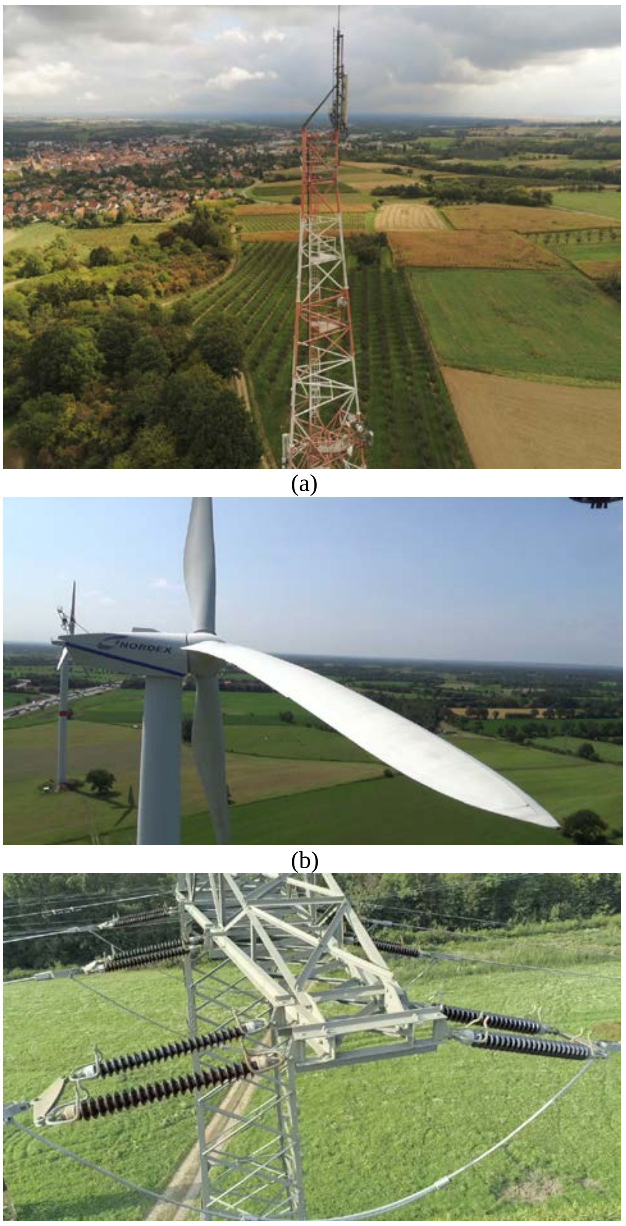
Figure 9: Visualization of image normalization.


(a) (b)

Figure 10: Normalized stereo images: (a) Left image, (b) Right image. The Tower is called "Tour de la Poudrière" or in English Powder Keg Tower which is the North east Corner of the historical City Wissembourg (France) and part of the City wall. It was built in the 14th century and also played a key role in the 8th century fortifications. This tall, square tower with capped levels (13th-14th centuries), open to the rear, controlled the north-east corner of the medieval curtain wall. It was still used as an observation post during the Second World War. Preceded by a bastion (for the atillery) in the 16th century, it remained a major element of the new fortifications of the 18th century. The rampart ditch was equipped with a lock so that it could be flooded. At the foot of the rampart, a vaulted underground passageway leads into the rue de la laine.

4. Conclusions

Inspection and maintenance of infrastructure elements are frequently outsourced to specialized service companies. When the expert team is not located near the infrastructure, they often need to travel significant distances to access the site and carry out their tasks. Furthermore, inspections may require close examination of critical components, which can involve physically demanding and risky activities, such as climbing walls or pillars or descending from heights using abseiling techniques (Figure 11).



(a)

(b)

(c)

Figure 11: Examples of several application areas for the REALTIME3Dsystem, (a) radio tower, (b) wind turbine, and (c) electricity tower.

REALTIME3D offers a practical solution that enables maintenance companies to conduct regular infrastructure inspections remotely, eliminating the need for site visits and reducing exposure to hazardous tasks. In addition to maintenance companies, the system is beneficial for public and private entities responsible for managing infrastructure, as well as organizations involved in monitoring and maintenance services. It is also suitable for any user requiring field visits or on-site observations for qualitative and quantitative assessments. By utilizing this system, users can minimize travel requirements while obtaining timely and highly detailed 3D data. Furthermore, the collected imagery can be archived for future reference and documentation, providing valuable records in case issues arise over time.

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