

Sandro Parrinello
Anna Dell'Amico

Salvatore Barba
Andrea di Filippo

editors

D-SITE

Drones - Systems of Information on Cultural Heritage
for a spatial and social investigation



D-SITE, Drones - Systems of Information on Cultural Heritage for a spatial and social investigation / Sandro Parrinello, Salvatore Barba, Anna Dell'Amico, Andrea di Filippo (edited by) - Pavia: Pavia University Press, 2022. - 684 p.: ill.; 21 cm.

(Prospettive multiple: studi di ingegneria, architettura e arte)

ISBN 978-88-6952-159-1
ebook 978-88-6952-160-7

The present publication is part of the series "Prospettive multiple: studi di ingegneria, architettura e arte", which has an international referee panel. "D-SITE, Drones - Systems of Information on Cultural Heritage for a spatial and social investigation" is a scientific text evaluated and approved by double blind peer review by the Scientific Editorial Board.

Translation of chapters and treatment of citations and bibliography are due to the respective authors.



Pavia University Press
Edizioni dell'Università degli Studi di Pavia
info@paviauniversitypress.it
www.paviauniversitypress.it

Copyright © 2022 EGEA S.p.A.
Via Salasco, 5 - 20136 Milano
Tel. 02/5836.5751 - Fax 02/5836.5753
egea.edizioni@unibocconi.it
www.egeaeditore.it

Editors
Sandro Parrinello, Salvatore Barba, Anna Dell'Amico,
Andrea di Filippo

Graphic project
Anna Dell'Amico, Francesca Picchio, Anna Sanseverino

On cover: Drawing by Francesca Picchio and Sandro Parrinello
First edition: june 2022.

Stampa: Logo S.r.l. – Borgoricco (PD)

The rights of translation, electronic storage, reproduction and even partial adaptation, by any means, are reserved for all countries.

The photocopies for personal use of the reader can not exceed 15% of each book and with payment to SIAE of the compensation provided in art. 68, c. 4, of the Law 22 of April of 1941, n. 633 and by agreement of December 18, between SIAE, AIE, SNS and CNA, ConfArtigianato, CASA, CLAAI, ConfComercio, ConfEsercenti. Reproductions for other purposes than those mentioned above may only be made with the express authorization of those who have copyright to the Publisher.

The volume consists of a collection of contributions from the conference "D-SITE, Drones - Systems of Information on Cultural Heritage for a spatial and social investigation". The event, is organized by the experimental laboratory of research and didactics DAda-LAB of DICAr - Department of Civil Engineering and Architecture of University of Pavia, and MODLab of DICIV - Department of Civil Engineering of University of Salerno. The publication co-funded by the the University of Pavia, the University of Salerno, and the Italian Ministry of Foreign Affairs and International Cooperation.

D-SITE CONFERENCE IS ORGANIZED BY:



UNIVERSITÀ
DI PAVIA

University of Pavia



DICAr - Department of Civil
Engineering and Architecture
University of Pavia



University of Salerno



DICIV - Department of Civil
Engineering
University of Salerno



DAda LAB - Drawing and
Architecture DocumentAction
University of Pavia



PLAY - Photography and 3D Laser
for virtual Architecture laboratory
University of Pavia



LS3D - Joint Laboratory
Landscape, Survey & Design
University of Pavia



Laboratorio Modelli -
Surveying and Geo-Mapping for
Environment and Cultural Heritage
University of Salerno

WITH THE PATRONAGE OF:



Ministero degli Affari Esteri
e della Cooperazione Internazionale

Italian Ministry
of Foreign Affairs and
International Cooperation



UID
Unione Italiana
Disegno



APEGA
Scientific Society
Expresión Gráfica Aplicada
a la Edificación



SIFET
Società Italiana
di Fotogrammetria
e Topografia



AIT
Associazione Italiana
di Telerilevamento



INGENIADRON

IN COLLABORATION WITH:



Università degli studi di Pavia
DIPARTIMENTO DI
SCIENZE DELLA TERRA
E DELL'AMBIENTE



Remote Sensing Laboratory of
the Department of Earth and
Environmental Sciences
University of Pavia

Department of Information
Engineering
University of Pisa



UNIVERSITÀ
DEGLI STUDI
FIRENZE

DAGRI
Dipartimento di
Geoscienze
e Ingegneria
della Terra,
dell'Ambiente
e del
Forestale

Department of Agricultural,
Food, Environmental and
Forestry Sciences
University of Florence



Istituto per il rilevamento
elettromagnetico dell'ambiente



Museum of Electrical
Technology
University of Pavia



Italian Ministry of Defence
Air Force



Italian National
Council of Engineers



Italian National Council of
Landscape Architects and
Conservators



Order of Engineers
Province of Pavia



Order of Landscape
Architects and Conservors
Province of Pavia

ENTERPRISE SPONSORS:



MEDIA PARTNERS:



LA PRIMA RIVISTA ITALIANA SUI DRONI



ORGANIZER COMMITTEES

Sandro Parrinello
Marco Limongiello

University of Pavia - Italy
University of Salerno - Italy

SCIENTIFIC COMMITTEES

Marcello Balzani
Salvatore Barba
José Antonio Barrera Vera
Stefano Bertocci
Carlo Bianchini
Mirco Boschetti
Enrico Borgogno Mondino
Stefano Campana
Massimiliano Campi
Gabriella Caroti
Filiberto Chiabrando
Gherardo Chirici
Antonio Conte
Krzysztof Cyran
Francesco Fassi
Francesca Fatta
Juan José Fernández Martín
Margherita Fiani
Andreas Fritz
Diego González-Aguilera
Armin Gruen
Pierre Grussenmeyer
Sorin Hermon
Xianfeng Huang
Marinos Ioannides
Falko Kuester
Francesco Mancini
Niccolò Menegoni
Luis M. Palmero Iglesias
Francesca Picchio
Lorenzo Pollini
Fabio Remondino
Fulvio Rinaudo
Mario Santana Quintero
Tesse D. Stek
Lina Tang
Dieter Tengen
Fabio Giulio Tonolo
Kyriacos Themistocleous
Rebeka Vital
Francesco Zucca

University of Ferrara - Italy
University of Salerno - Italy
University of Seville - Spain
University of Florence - Italy
La Sapienza, University of Rome - Italy
IREA, CNR - Italy
University of Turin - Italy
University of Siena - Italy
University of Naples Federico II - Italy
University of Pisa - Italy
Polytechnic of Turin - Italy
University of Florence - Italy
University of Basilicata - Italy
Silesian University of Technology - Poland
Polytechnic of Milan - Italy
University of Reggio Calabria - Italy
University of Valladolid - Spain
University of Salerno - Italy
University of Freiburg - Germany
University of Salamanca - Spain
ETH Zurich Faculty of Architecture - Swiss
Institut National des Sciences Appliquées - France
The Cyprus Institute - Cyrus
Wuhan University - Hubei China
Cyprus University of Technology - Cyprus
University of California - USA
University of Modena and Reggio Emilia - Italy
University of Pavia - Italy
Polytechnic of València - Spain
University of Pavia - Italy
University of Pisa - Italy
Bruno Kessler Foundation - Italy
Polytechnic of Turin - Italy
Carlton University - Canada
Leiden University - Netherlands
Chinese Academy of Sciences - Cina
Technical University Braunschweig - Germany
Polytechnic University of Turin - Italy
Cyprus University of Technology - Cyprus
Shenkar College of Engineering and Design - Israel
University of Pavia - Italy

SCIENTIFIC SECRETARIAT

Anna Dell'Amico (University of Pavia), Andrea di Filippo (University of Salerno), Silvia La Placa (University of Pavia)

INDEX

PREFACE

SANDRO PARRINELLO, ANNA DELL'AMICO

Drones and Digital Innovation: a new scenario in Digital Dimension

16

CONFERENCE PAPERS

CATERINA PALESTINI, ALESSANDRO BASSO, MAURIZIO PERTICARINI

3D modeling from UAV for the reconfiguration of oxidation systems in Abruzzo.

28

The case of the tower of Forca di Penne, an immersive archival resource for the lost Historical Heritage

RAMONA QUATTRINI, RENATO ANGELONI, BENEDETTA DI LEO

Data integration and optimization for Cultural Heritage fruition. The case study of the Rail to Land Project

38

ANDREA PIRINU, RAFFAELE ARGOLAS, NICOLA PABA

Design models and landscape form of Sardinian IWW Heritage. The Simbirizzi Lake in territory of Quartu Sant'Elena

48

MARCO SACCUCCI, VIRGINIA MIELE, ASSUNTA PELLICCIO

UAVs for the analysis of geometrical deformation of fortresses and castles. The case study of Sora Castle

58

RITA VALENTI, EMANUELA PATERNÒ, GRAZIELLA CUSMANO

UAS applications for the protection of archaeological heritage. From the interpretative complexity of the absence to 3D visualization of euryalus castle

66

Giovanni Pancani, Matteo Bigongiari

The aerial photogrammetric survey for the documentation of the Cultural Heritage:
the Verruca fortress on the Pisan Mountains

76

ELENA MADALINA CANTEA, ANNA DELL'AMICO		
Application of fast survey technologies for knowledge, valorization and conservation: the case study of Rondella delle Boccare	84	
PIETRO BECHERINI, ROLANDO VOLZONE, ANASTASIA COTTINI		
A 3D model for architectural analysis, using aerial photogrammetry, for the digital documentation of the convent of Santa Maria da Insua, on the northern border between Portugal and Spain	94	
ALBERTO PETTINEO		
Videogrammetry for the virtual philological reconstruction of the Scaliger fortifications in the territory of Verona. The case study of Montorio Castle	104	
GIULIA PORCHEDDU, FRANCESCA PICCHIO		
Close-Range Photogrammetry for the production of models and 3D GIS platform useful for the documentation of archaeological rescue excavations	112	
FABRIZIO AGNELLO, MIRCO CANNELLA		
Multi sensor photogrammetric techniques for the documentation of the ruins of Temple G in Selinunte	122	
GIANLUCA FENILI, GIORGIO GHELFI		
Conservation and enhancement of Cultural Heritage using UAVs. New perspectives for the preservation of some case studies	130	
CATERINA GRASSI, DIEGO RONCHI, DANIELE FERDANI, GIORGIO FRANCO POCOBELLI, RACHELE MANGANELLI DEL FA'		
A 3D survey in archaeology. Comparison among software for image and range-based data integration	138	
GIORGIA POTESTÀ, VINCENZO GELSONIMO		
Experience of integrated survey by drone for archaeological sites. Documentation, study, and enhancement of the Italic Sanctuary of Pietrabbondante	146	
CÈLIA MALLAFRÈ-BALSELLS, DAVID MORENO-GARCIA, JORDI CANELA-RION		
Photogrammetric comparison between different drone survey methodologies: dry stone as a case study	156	
DIEGO MARTÍN DE TORRES, JULIÁN DE LA FUENTE PRIETO, ENRIQUE CASTAÑO PEREA		
Scars in the landscape: photogrammetry and analysis of the trenches of the Spanish Civil War	168	
SALVATORE BARBA, ALESSANDRO DI BENEDETTO, MARGHERITA FIANI, LUCAS GUJSK, MARCO LIMONGIELLO		
Automatic point cloud editing from UAV aerial images: applications in archaeology and Cultural Heritage	176	
CORRADO CASTAGNARO, DOMENICO CRISPINO		
Drone flight as a knowledge tool for Cultural Heritage	184	
ELENA GÓMEZ BERNAL, PABLO ALEJANDRO CRUZ FRANCO, ADELA RUEDA MÁRQUEZ DE LA PLATA		
Drones in architecture research: methodological application of the use of drones for the accessible intervention in a roman house in the Alcazaba of Mérida (Spain)	192	

LORENZO TEPPATI LOSÈ, FILIBERTO CHIABRANDO, ELEONORA PELLEGRINO UAS photogrammetry and SLAM for the HBIM model of the Montanaro Belltower	202
FABIANA GUERRERO Methodologies for the protection of the Portuguese architectural heritage	212
CARLO COSTANTINO, ANNA CHIARA BENEDETTI, GIORGIA PREDARI UAV photogrammetric survey as a fast and low-cost tool to foster the conservation of small villages. The case study of San Giovanni Lipioni	220
LUCA VESPASIANO, LUCA CETRA, STEFANO BRUSAPORCI Experience of Indoor Droning for Cultural Heritage Documentation	232
RICCARDO FLORIO, RAFFAELE CATUOGNO, TERESA DELLA CORTE, VICTORIA COTELLA, MARCO APREA Multi-source data framework: integrated survey for 3D texture mapping on archaeological sites	240
VALERIA CERA, MASSIMILIANO CAMPÌ Evaluation of unconventional sensors for the photogrammetric survey of underwater historical sites	250
DJORDJE DJORDJEVIC, MIRJANA DEVETAKOVIC, DJORDJE MITROVIC Regulatory and controlling mechanisms on UAV/UAS that influence efficient architectural heritage praxis: actual situation in Serbia	260
ANTONIO CONTE, ANTONIO BIXIO Privileged documentary observations of surveying of “fragile heritage” in emergency conditions: the case studies of Pomarico landslide and of Montescaglioso abbey	270
MARCO CANCIANI, MARCO D’ANGELICO A methodology for survey, documentation and virtual reconstruction of historical centers in a seismic area: the case study of Arquata del Tronto	280
RAISSA GAROZZO, DAVIDE CALIÒ, MARIATERESA GALIZIA, GIOVANNA PAPPALARDO, CETTINA SANTAGATI Integration of remote surveying methodologies for geological risk assessment of masonry arch bridges	294
FAUSTA FIORILLO, LUCA PERFETTI, GIULIANA CARDANI Aerial-photogrammetric survey for supervised classification and mapping of roof damages	304
RAFFAELLA DE MARCO, ELISABETTA DORIA The processing of UAV 3D models for the recognition of coverages at the technological scale: opportunities for a strategy of conservation monitoring	314
QIUYAN ZHU, SHANSHAN SONG, LINGYUN LIAO, MARIANNA CALIA, XIN WU UAV survey for documentation and conservation of Han City in the UNESCO mixed heritage site of Mount Wuyi, China	324

ZHUOWEI LIN, MARIANNA CALIA, LINGYUN LIAO, XIN WU Digital survey of the Cliff-Burial sites with consumer-level UAV photogrammetry: a case study of Mt. Wuyi	334
ANNA SANSEVERINO, CATERINA GABRIELLA GUIDA, CARLA FERREYRA, VICTORIA FERRARIS Image-based georeferenced urban context reconstruction in a BIM environment: the case of the Crotone Fortress	344
ANDREA ARRIGHETTI, ALFONSO FORGIONE, ANDREA LUMINI The Church of San Silvestro in L'Aquila. An integrated approach through TLS and UAV technologies for the architectural and archaeological documentation	356
SILVIA LA PLACA, FRANCESCA PICCHIO Fast survey technologies for the documentation of canalization systems. The case study of the settlement "Il Cassinino" in the Naviglio Pavese surrounding	366
TOMMASO EMPLER, ADRIANA CALDARONE, MARIA LAURA ROSSI Fast assessment survey for protected architectural and environmental site	376
MASSIMO LESERRI, GABRIELE ROSSI Salento baroque spires survey. Integrating TLS and UAV photogrammetry	386
SARA ANTINOZZI, ANDREA DI FILIPPO, ANGELO LORUSSO, MARCO LIMONGIELLO Toward a virtual library experience based on UAV and TLS survey data	396
GENNARO PIO LENTO UAS applications for the survey of monumental architecture. The case study of the Royal Residence of Aranjuez in Spain	404
ORNELLA ZERLENGA, GIANFRANCO DE MATTEIS, SERGIO SIBILIO, GIOVANNI CIAMPI, VINCENZO CIRILLO, ET AL. Open source procedure for UAV-based photogrammetry and infrared thermography in the survey of masonry bell towers	412
TOMÁS ENRIQUE MARTÍNEZ CHAO, GIUSEPPE ANTUONO, PEDRO GABRIEL VINDROLA, PIERPAOLO D'AGOSTINO Image-based segmentation and modelling of terraced landscapes	422
ALESSIO CARDACI, PIETRO AZZOLA, ANTONELLA VERSACI The Astino Valley in Bergamo: multispectral aerial photogrammetry for the survey and conservation of the cultural landscape and biodiversity	432

RAFFAELA FIORILLO, ANGELO DE CICCO The Port of Fiskardo: architecture, history and innovation	442
GUIYE LIN, PABLO ANGEL RUFFINO, LU XU, ANDREA GIORDANO, LUIGI STENDARDO, RACHELE A. BERNARDELLO Application of UAV photogrammetry technology in the process of architectural heritage preservation	450
EMANUELE GARBIN On phenomenology of remote vision: the panoramas of the first lunar probes	458
FRANCESCA GALASSO, ALESSIA MICELI The documentation of the decorative system of the Ark of Mastino II in Verona. Comparative analysis of photogrammetric data obtained from UAV systems	468
VALENTINA CASTAGNOLO, ANNA CHRISTIANA MAIORANO, REMO PAVONE Immersive environments and heritage digitization. The virtual image of a medieval cathedral	478
LUCA FORMIGARI, VERONICA VONA, MARCO ZUPPIROLI Towards an "allround" control of the restoration project: 3D modelling as a real-time monitoring system for the design outcome	488
DAVIDE CARLEO, MARTINA GARGIULO, GIOVANNI CIAMPI, MICHELANGELO SCORPIO, PILAR CHIAS NAVARRO Immersive virtual model accuracy and user perception: preliminary results of a case study with low cost photogrammetric survey method by drone	500
HANGJUN FU UAV survey for 3D printing digital modeling for the representation and enhancement of Nativity Church on the urban and architectural scales	510
CHIARA RIVELLINO, MARCO RICCIARINI Testing the reliability of mini-UAVs acquisition campaign on detailed bas-reliefs. The case study of sculpturing elements of Donatello's Pulpit	518
ANDREA CAMPOTARO Documenting the evolution of a Lilong neighborhood in contemporary Shanghai through mini-UAV-based photogrammetry surveys	528
CRISTIANA BARTOLOMEI, CECILIA MAZZOLI, CATERINA MORGANTI The Woodpecker: virtual reconstruction of an abandoned discotheque in the Adriatic Coast	536
YLENIA RICCI, ANDREA PASQUALI From UAV photogrammetry to digital restitution, new process for the preservation of Cultural Heritage	544

REMOTE SENSING IN AGRICULTURE AND FORESTRY	556
CLAUDIO SPADAVECCHIA, ELENA BELCORE, MARCO PIRAS, MILAN KOBAL Forest change detection using multi-temporal aerial point clouds	558
RAMIN HEIDARIAN DEHKORDI, MIRCO BOSCHETTI Exploring the relationship between soil organic carbon and crop water stress across century-old biochar patches within agricultural fields by combining UAV thermal, multispectral, and RGB images	564
GIORGIO IMPOLLONIA, MICHELE CROCI, ANDREA MARCONE, GIULIA ANTONUCCI, HENRI BLANDINIÈRES, STEFANO AMADUCCI UAV-based remote sensing to evaluate nitrogen and irrigation effects on LAI and LCC dynamics combining PROSAIL model and GAM	570
CARLOS CARBONE, MULHAM FAWAKERJI, VITO TRIANNI, DANIELE NARDI Photorealistic simulations of crop fields for remote sensing with UAV swarms	576
BIANCA ORTUANI, ALICE MAYER, GIOVANNA SONA, ARIANNA FACCHI Use of vegetation indices from Sentinel2 and UAV in precision viticulture applications	582
FILIPPO SARVIA, SAMUELE DE PETRIS, ALESSANDRO FARBO, ENRICO BORGOGNO MONDINO Geometric vs Spectral content of RPAS images in the precision agriculture context	588
GIOVANNA SCARDAPANE, FEDERICA MASTRACCI, ANTONELLO CEDRONE, LILIAN VALETTE T-DROMES®, Drone-as-a-Service solutions for Smart Farming	596
FRANCESCA GIANNETTI, GIOVANNI D'AMICO, FRANCESCO CHIANUCCI, GHERARDO CHIRICI UAV forest application supporting sustainable forest management	602
GEOLOGY AND UAV: RESEARCH, EXPERIENCES AND FUTURE PERSPECTIVES	608
ALBERTO BOSINO, NICCOLÒ MENEGONI, ELISA FERRARI, CLAUDIA LUPI, CESARE PEROTTI Art and Drones: retracing the paths of Torquato Taramelli 100 years later	610
NICCOLÒ MENEGONI, DANIELE GIORDAN, CESARE PEROTTI, ENRICO ARESE Uncrafted Aerial Vehicle-based rock slope stability analysis of Baveno granite quarry area: the tailing and waste rock extractive site of Ciana-Tane Pilastretto (Montorfano)	614
DAVIDE FUGAZZA, MARCO SCAIONI, VALERIA BELLONI, MARTINA DI RITA, FABIANO VENTURA, FABRIZIO TROILO, GUGLIELMINA ADELE DIOLAIUTI UAVs in cryospheric studies: experiences from Alpine glaciers	620

MARCO LA SALANDRA	
Application of UAV system and SfM techniques to address the hydro-geomorphological hazard in a fluvial system	622
DANIELE GIORDAN, MARTINA CIGNETTI, DANILO GODONE, ALEKSANDRA WRZESNIAK	
Structure from motion multi-source application for landslide characterization and monitoring	626
FABRIZIO TROILO, NICCOLÒ DEMATTEIS, DANIELE GIORDAN, FRANCESCO ZUCCA	
UAV observation of the recent evolution of the Planpincieux glacier (Mont Blanc)	628
MARCO DUBBINI, CORRADO LUCENTE, GIACOMO UGUCCIONI	
Photogrammetric monitoring by drone of San Leo landslide (Rimini)	630
AERIAL, GROUND AND UNDERWATER ROBOTICS FOR CULTURAL HERITAGE	
MATHEW JOSE POLLAYIL, FRANCO ANGELINI, MANOLO GARABINI	632
UAV for environmental monitoring	634
DANILA GERMANESE, DAVIDE MORONI, MARIA ANTONIETTA PASCALI, MARCO TAMPUCCI, ANDREA BERTON	
Exploring UAVs for structural health monitoring	640
BENEDETTO ALLOTTA, ALESSANDRO RIDOLFI, NICOLA SECCIANI	
Autonomous Underwater Vehicles for Underwater Cultural Heritage: some experiences from the University of Florence	644
FABIO BRUNO, ANTONIO LAGUDI, UMBERTO SEVERINO	
Autonomous Surface Vehicles to support underwater archaeologists in survey and documentation	648
FABRIZIO GIULIETTI, EMANUELE LUIGI DE ANGELIS, GIANLUCA ROSSETTI, MATTEO TURCI	
High-range/high endurance rotary wing aircraft for environmental protection and Cultural Heritage valorisation	652
AFTERWORD	
SALVATORE BARBA, ANDREA DI FILIPPO	658
DICIV - Department of Civil Engineering	
SPONSOR	
	664



RICCARDO FLORIO, RAFFAELE CATUOGNO, TERESA DELLA CORTE, VICTORIA COTELLA, MARCO APREA

University of Naples Federico II
Naples, Italy

riccardo.florio@unina.it

Keywords:
Integrated survey, Archaeology, UAV, TLS, Thermal imaging.

ABSTRACT

The aim of the present research is to test an integrated framework between the data obtained from the Unmanned Aerial Vehicle (UAV), a handheld thermographic camera (Infrared thermography) and the Terrestrial Laser Scanner (TLS).

Piscina Mirabilis, in the city of Naples, becomes the benchmark to generate a comprehensive database, including a clear geometrical definition of the thermal variations of the wall surfaces by texturing the IR images directly on the RGB mesh surfaces. To measure the performance of mapping, the present research compared the quality of information by using 3D processing algorithms to optimise final the result.

MULTI-SOURCE DATA FRAMEWORK: INTEGRATED SURVEY FOR 3D TEXTURE MAPPING ON ARCHAEOLOGICAL SITES

1. INTRODUCTION

1.1. LITERATURE REVIEW: 3D THERMAL MAPPING AND UAV IN THE CULTURAL HERITAGE FIELD

Infrared thermography (IRT) is a widely used non-destructive method for energy audits.

However, considerable research indicates that the performance of thermography is influenced by the method of data acquisition (Hou et al., 2019).

The use of IRT images is playing an important role because heat loss from buildings can be easily detected and visualized by thermal cameras. In fact, for detailed inspections of small areas, terrestrial images can be taken manually, while for surveys of larger areas mounting IR cameras on an unmanned aerial vehicle (UAV) is an alternative option. Terrestrial image acquisition methods can provide detailed information on the smallest areas (Lin et al., 2018).

Unmanned aerial vehicles (UAVs) have been successfully employed to perform RGB photogrammetry to reduce the time and complexity of data collection.

But the data collected by an infrared thermal camera and an optical camera differ from each other in terms of the level of resolution: the data collected by the optical camera are considered to have a higher resolution.

On the other hand, the infrared thermal camera usually has a lower display resolution, is more likely to be influenced by environmental conditions and is limited by the distance between the camera and the objects (Mayer et al., 2021). Thermal texture mapping, which maps thermal images onto existing 3D geometric data,

allows thermal images to be spatially referenced and thermal patterns to be accurately interpreted.

Due to large image overlaps, each face of a building model often corresponds to several thermal images.

Researchers are exploring different thermal texture mapping approaches focusing on the automation of texture selection: (Wang, 2008) combined object incident angle and visibility analysis to select textures from oblique images.

To differentiate components' semantic information (semantic segmentation) and to delineate each distinct object (instance segmentation), many computer vision algorithms - especially deep learning approaches - have been developed, such as Mask R-CNN (He, et al., 2020), the YOLO family (Wong et al., 2019), and the DeepLabfamily (Chen, et al., 2018). Finally, Chizhova and Korovin (Chizhova et al., 2017) improved the geometric matching accuracy of their model-to-image registration method by taking uncertainties of the 3D building model and image features into consideration. Therefore, thermal radiant characteristics are taken into consideration. To measure the performance of texture mapping, this research compared the quality of images generated from a 3D point cloud model constructed by UAV and TLS acquired data with images acquired directly from a handheld thermal camera.

The comparisons were based on quality and efficiency in the data acquisition phase, and different factors' influences.

The following sections will present the goals and case of study, materials, research methods, discussion of the results and final conclusions.

1.2. AIMS OF THE PROPOSAL AND CASE OF STUDY

The present work seeks to determine a workflow to map the IR images with TLS and UAV data.

For this reason, it was considered necessary to integrate different techniques and sources of information in order to optimise the results and reduce the margin of error.

The main issue is that thermal camera resolution is not as high as the optical camera's resolution resulting in a lower quality 3D model generated by photogrammetry mapping. The benchmark of the experimentation is the Piscina Mirabilis (Figure 1), the final reservoir of the "Serino aqueduct" in the city of Naples. (De Feo, 2007).

The aqueduct filled several points in the Campi Flegrei area to finally reach the end of the path: the Piscina Mirabilis.

This building is a gigantic water reservoir of 72 m long and 27 m wide with a height of 15 m., which operated

through a series of gates that opened and closed along with the vaults in the central nave; the water was lifted by hydraulic machines over the opening terrace of the covered cistern. (De Feo, 2010)

Forty-eight pillars, presented in four rows supporting the barrel vaults, divide the space into five main naves on the long sides and thirteen secondary naves on the short sides, giving it the majestic appearance of a cathedral, hence its name, "The cathedral of water".

Today, the building is in a visible state of degradation and the creation of an integrative database could be considered a solution to manage the monitoring and restoration activities.

Based on these assumptions the subsequent sections of the manuscript are specifically aimed at proving the research procedure adopted.

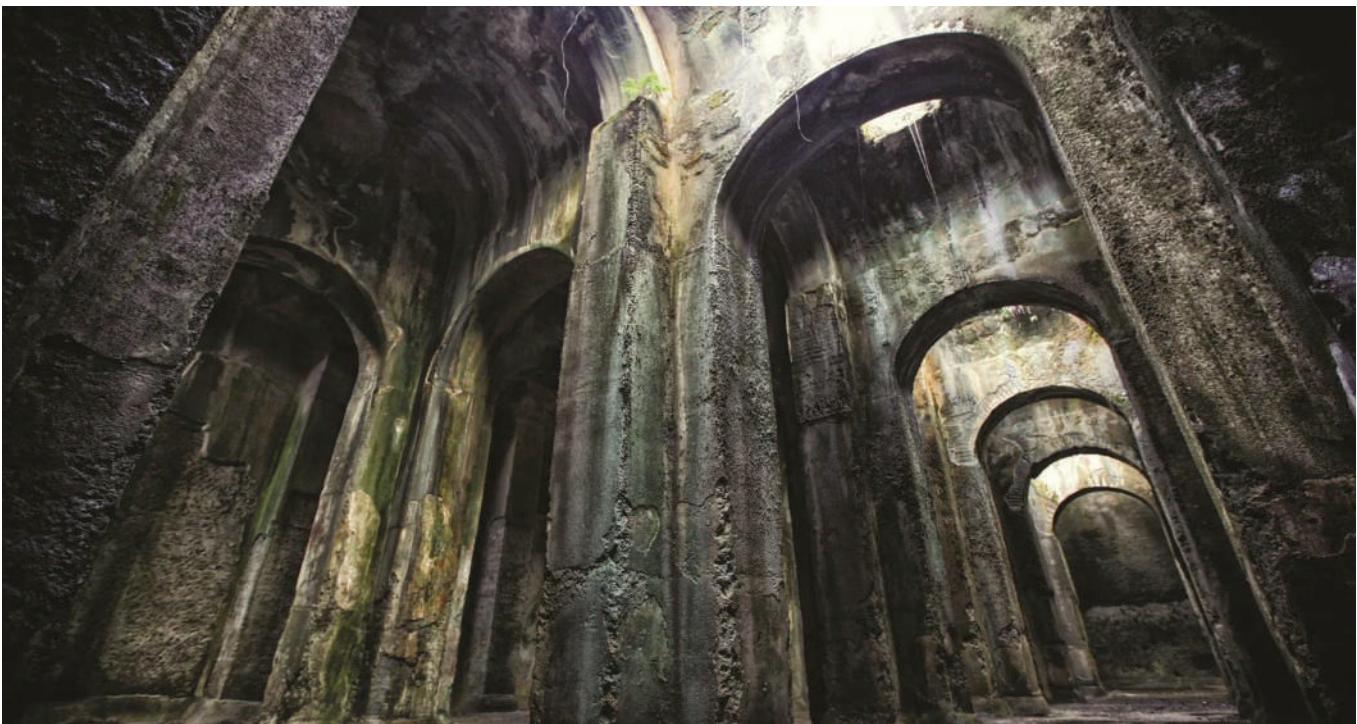


Figure 1. Internal view of the Piscina Mirabilis in the current state. Source: Fondo Ambiente Italiano, Piscina Mirabilis, <https://fondoambiente.it/lughi/piscina-mirabilis>.

2. MATERIALS

2.1. FARO Focus 3D X330

Faro Focus 3D X330 is a stationary laser scanner with integrated digital color camera.

The range-based modelling method employs techniques based on active sensors, using laser scanners that emit electromagnetic signals recorded by a sensor in order to derive a distance (range) measurement.

This solution guarantees an accuracy of ± 2 mm in a range of 0.6 m up to 130 m.

2.2. DJI PHANTOM 4

The UAV has an approximate weight of 1.4 kg. Its camera is equipped with a 12 MP Sony Exmor sensor and a wide-angle lens with a 4 mm focal length and FOV (Field of View) of 94°.

With a flight autonomy of almost 30 minutes the drone can fly at a maximum speed of 70 km/h.

The camera is integrated in a gimbal to maximize the stability of the images during the movements, being able to acquire videos in 4K definition.

2.3. FLIR E40bx

This Thermal Camera has a 160x120-pixel resolution providing thermal images that clearly display building conditions.

The advanced MSX imaging feature adds even more texture and detail to these images, allowing quicker fault location.

With a low thermal sensitivity capable of detecting temperature differences as low as 0.045°C , the FLIR E40bx enables users to accurately diagnose anomalies.

The camera is in fact equipped with two separate optical systems for acquiring the thermal image and the corresponding image in real colors.



Figure 2. Design of a vertical section. Source: Avanzi della Antichità esistenti a Pozzuoli, Cuma, e Baia by Paolo Antonio Paoli, by Giovanni Volpatto (1735-1803).

3. RESEARCH METHODS

3.1. SURVEY DESIGN AND DATA COLLECTION

3.1.1. TLS

A survey design should first define TLS station locations to ensure complete coverage of the object at the required spatial resolution.

Considering the main dimensions of the interior space of the Piscina Mirabilis (on the horizontal plane the maximum extensions are 72 m x 25 m, and the internal height is 15 m) (Figure 2) with a total of 48 columns distributed in 4 rows of 12 columns, the instrument was set to have a resolution of 6 mm in 10 m. Basically, in order to avoid areas of occlusion generated by the number of pillars, as a general criterion, it was decided to make one scan for each bay. In the outside, the resolution was changed to 10 mm in 10 m, placing the

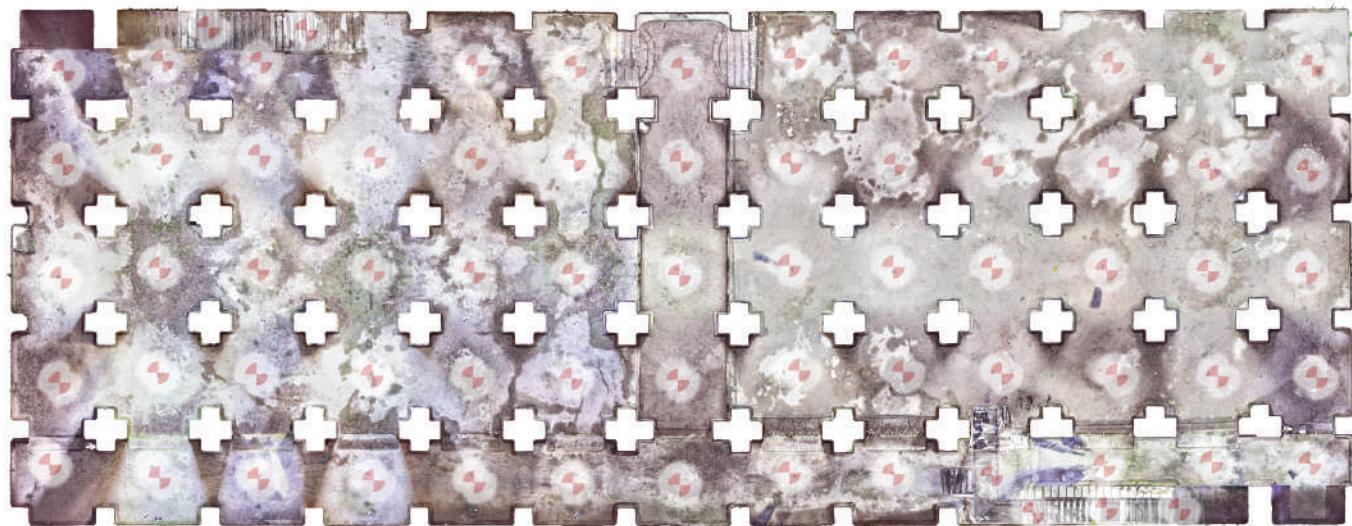


Figure 3. Floor plan extracted from the point cloud processed, with the interior TLS stations.

stations on the external street with a distance of 5 m. defined by the spacing between columns.

Finally, In the entrance sector, it was necessary to make 3 stations that allowed linking the data acquired on the inside and outside of the building.

With a total of 75 internal scans and 17 external scans, the TLS acquisition campaign has taken almost 10 hours, with a single-scan time of approximately 6 minutes and 30 seconds (Figure 3).

3.1.2. UAV

Due to the high elevation of Piscina Mirabilis (15 m), it was necessary to integrate the data acquired with the laser scanner. The geometrical acquisition of the upper vaults was not optimal because the insufficient illumination inside the environment did not allow an optimal acquisition of the color deducible from the projection of the panoramic image obtained with the laser scanner camera. Therefore, it was decided to merge the data using aerial photogrammetry, which, although less precise than the techniques based on

active sensors, allows to control the parameters related to the exposure and the position of the shooting point. Considering that the study site to be treated is located at the underground level, it was already anticipated to carry out a manual flight because it would be impossible to connect the UAV to the GPS network. Consequently, the study area was reduced to the vaults adjacent to the side walls of the Piscina Mirabilis (Figure 4) in order to merge the information with infrared data to be acquired.

For the acquisition of the internal frames, two types of manual flights were designed: a first one for the acquisition of nadir photogrammetric images and a second one, with the optical axis tilted about 45°, to survey any shadow cones.

As expected, the quality of the data taken was not optimal since the drone presented stabilisation problems due to the missing connection to the GPS network and it was not able to fly at the expected height.

A total of 180 images were taken at 90°, while 235 images were taken at 45°, with a grand total of 415

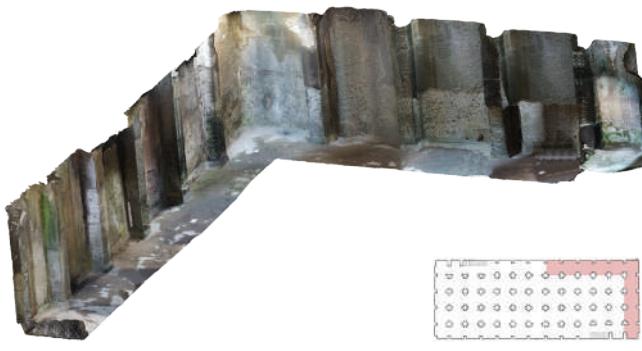


Figure 4. Axonometric view as a result of the photogrammetric process, with the study area highlighted in color.

internal images and an overlapping of 80% in the first case and 70% in the second case. On the other hand, for the external data acquisition, the instrumentation worked correctly, allowing the loading of the flight plan previously designed in the DJI Terra software (Figure 5). Another two flights missions are programmed: a first nadir flight and a second oblique flight, both having an image overlap of 70% as well as sidelap of 70% in a total area of 2550 m² approximately.

In the nadir flight, 74 images were acquired for the first grid, at a flight route distance of 353 meters and a flight time of 4 min and 35 s. After that, an oblique flight with the camera tilted at 45° on the horizontal plan, was carried out acquiring 143 photos in 5 minutes and 26 seconds.

3.2 INFRARED THERMOGRAPHY

In order to obtain a comprehensive representation of the anomalies present in the Piscina Mirabilis, thermographic data have been acquired through relevant instruments that have to investigate the



Figure 5. Oblique flight mission setup in DJI Terra software.

reflective and emissive response of the surface examined in different bands of the integrated spectrum, providing auxiliary instructions compared to traditional methods. The goal, as mentioned before, is to incorporate the differences in temperature obtained with the infrared camera.

For this reason, it was decided to continue working with the lateral zone of the monument, which presented a greater amount of masonry mass and therefore, a greater level of degradation to analyze.

A total of 182 images with a 160x120-pixel resolution were taken inside the building (Figure 6), obtaining as a result the IR and its corresponding RGB image.

Since this is a largely underground area, the temperature of the lateral walls varies between 5 and 9 degrees Celsius (41 and 48.2 Fahrenheit), increasing proportionally according to the amount of wall mass or the proximity to the outside, where the temperature is higher. However, despite the proximity of the user to the object of study (2 m), it was not possible to reproduce the degradation pathologies with an optimal level of detail.

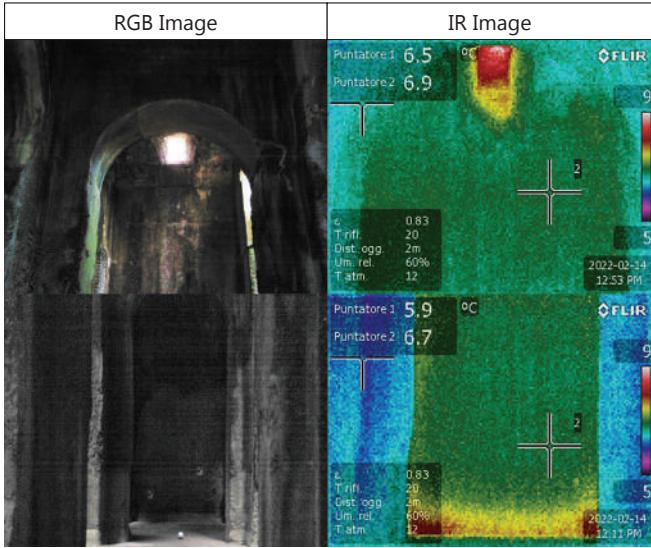


Figure 6. Comparison between the RGB image and the corresponding IR image, where the temperature is higher on the side walls.

3.3 DATA PROCESSING: POINT CLOUD REGISTRATION

3.3.1 TLS SCAN REGISTRATION

These data were, indispensable to align the photogrammetric data. The clouds are characterized by a high degree of overlap (60%) and for this reason are registered employing a global bundle adjustment procedure, accomplished after a top view-based and cloud-to-cloud preregistration (Figure 7).

Given the set of scans, the algorithm searches for all the possible connections between the pairs of point clouds with overlap.

For each connection, a pairwise ICP is performed and the best matching point pairs between the two scans are saved. A final non-linear minimization is run only among these matching point pairs of all the connections. The global registration error of these point pairs is minimized, having as unknown variables the scan poses (Barba et al., 2021).

The RMSE on the registration is about 1,2 mm and the maximum value is 2,2 mm.

3.3.2 UAV ORTHOIMAGES REGISTRATION

Agisoft Metashape software was used for the photogrammetric data processing phase. Initially, all frames were grouped into a single chunk. Due to the similar geometrical characteristics of the building, it was necessary to add makers as control points for an easier recognition of homologous points in the different images.

The operations performed by the software are based on Structure from Motion (SfM) using algorithms such as SIFT (Scale-invariant feature transform) and SURF (Speeded Up Robust Features) that extract the significant points or tie points, homologues in different frames and identify the internal and external orientation parameters (Lowe, 2004).

With the data calculated by triangulation, the software created a first sparse point cloud. In the next step, Dense Image Matching (DSM) algorithms build a Triangulated Irregular Network (TIN) and a B-Rep (Boundary Representation) model is obtained.

Finally, it was possible to combine the photogrammetric data with that obtained by the laser scanner resulting in an integrated point cloud of the exterior and interior of the Piscina Mirabilis.

3.4 DATA ANALYSIS: 3D TEXTURE MAPPING

To calculate the differences and errors between merged two images (IR and RGB), two mathematical approaches were used being Mean Squared Error (MSE) and Structural Similarity Measure (SSM). Shown in equation (1) and equation (2) (Hou et al., 2019).

$$MSE = \frac{1}{mn} \sum_{i=0}^{m-1} \sum_{j=0}^{n-1} [I(i, j) - K(i, j)]^2 \quad (1)$$

$$SSIM = \frac{(2\mu_x \mu_y + c_1)(2\sigma_{xy} + c_2)}{(\mu_x^2 + \mu_y^2 + c_1)(\sigma_x^2 + \sigma_y^2 + c_2)} \quad (2)$$



Figure 7. Partial cross-section showing the central part of the Piscina Mirabilis, as a result of TLS data processing in FARO Scene software.

MSE checks difference of every two relative pixels in two images. It squares these differences, sums them up and divide the sum of squares by the total number of pixels in the images. An MSE of value 0 indicates that two pictures are perfectly identical. The greater the value of MSE is, the more errors rendered pictures create. On the other hand, SSIM method can perceive changes in small sub-samples, whereas MSE estimates the perceived errors in the entire images. In equation two, (x, y) indicates the $N \times N$ sub-window in each image, and SSIM can be calculated on various windows of an image. The SSIM value can range between -1 and 1, where 1 represents perfect identicity. With the basis on these assumptions, in the present research the criterion of comparison was to calculate the differences and errors between RGB and IR images in 2 different scenarios presented in Table 1: First, with images taken at 90 degrees and second with images at 45 degrees. Different factors were tested: Flight grid, angle in the UAV flight pattern, overlap of images, number of aligned

images, distance of the camera from the object under study and finally the height of the IR camera held by the user.

4. RESULTS AND DISCUSSION

Two comparison cases were tested, as presented in Table 1. In scenario 1, the flight was developed with the UAV camera angle at 90° with respect to the side walls (Figure 8). The image on the left presents the IR image and the picture on the right shows the RGB data as a result of integrated point cloud reconstruction.

To test the color rendering performance and structure similarity performance in the texture mapping process, the MSE and SSIM values are calculated (Fig 9.). Mapping process in images of a model with a flight camera angle of 90° (scenario 1) was better than rendering images of a model with a flight camera angle of 45° in terms of capturing color information, since scenario 1 had a lower MSE score. The MSE value in scenario 2 was

Scenario Number	Flight Grid	Camera Angle	Image Overlap	Number of aligned images	Mean Reprojection Error [pixels]	IR Camera Distance	IR Camera Height
Scenario 1	Complete Grid	90°	80%	180 of 180	0.198	2 m	1.7 m
Scenario 2	Complete Grid	45°	70%	213 of 235	0.203	4 m	1.7 m

Table 1. Summary of different factors to be tested in both cases.

5.25941 which can be considered an outlier, since the MSE values varied from 0 to 1.

Factors influencing the higher MSE value for scenario 2 is the distance and different angulation between the image taken by the UAV and that taken with the handheld thermal camera, obviously determined by the height of the user. Also, although the number of photos was higher, the overlap between images was lower than in scenario 2: because of this, Metashape software was not able to align all the images and therefore they were not processed.

5. Conclusions

Thermography has been introduced in a number of research fields, most notably, it has been used to capture the energy loss of a single building. However, creating a 3D thermal model with high resolution for asset restoration remains a challenge in terms of efficiency and performance.

Regarding the UAV flight, a camera angle of 90 degrees could capture more details on the internal walls or exterior flat roof system, while a camera flight angle of 45 degrees is more suitable for capturing details of the internal vaulted system, which presents a complex geometry.

In terms of image overlap, a larger number of thermal images could introduce more potential outliers. In addition, the quality of the images taken must be taken into account. Using a handheld camera, where the

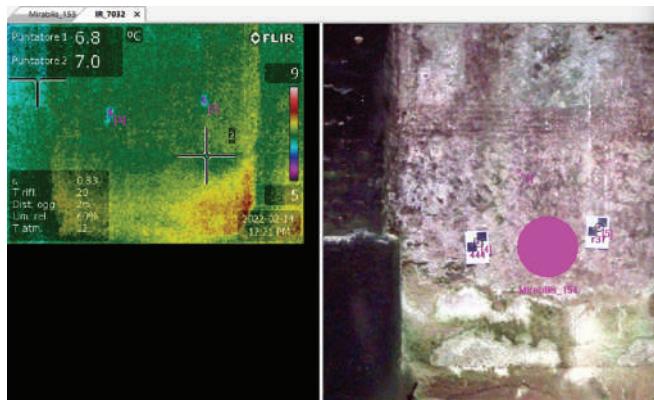


Figure 8. Comparison both images (IR and RGB) in the case 1.

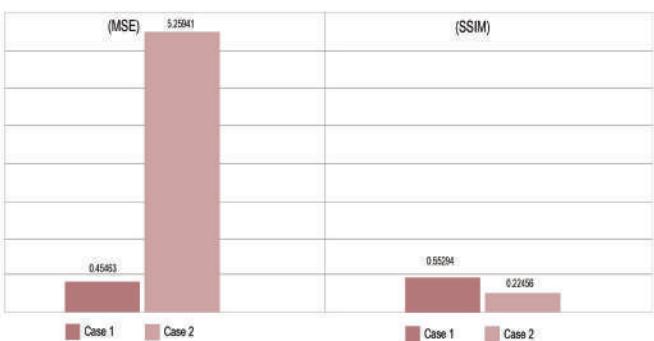


Figure 9. Statistics of MSE, and SSIM for both scenarios.

images are taken by the user, it is impossible to achieve a match between the angles of the images acquired by the UAV. If both RGB and IR images can be captured from the same angles and altitudes, a detailed 3D model can be created using high resolution RGB images, and then thermal textures can be projected onto the 3D model achieving a higher final accuracy.

Future prospects include the acquisition of data using UAVs with a thermal camera included to eliminate the problem of the angle difference between photos, which is a main factor influencing the efficiency and performance of 3D thermal mapping. In addition, it is also expected to face the problem of stabilization of the drone in areas without GPS signal, thus being able to optimize the data processing phase by applying automatic processing algorithms.

BIBLIOGRAPHY

Barba S., di Filippo A., Cotella V., Ferreyra C., & Amalfitano S. (2021). *A SLAM Integrated Approach for Digital Documentation. Culture and Computing*. Interactive Cultural Heritage and Arts, 9th International Conference, C&C 2021, Held as Part of the 23rd HCI International Conference, HCII 2021, Virtual Event.

Chen L., Papandreou G., Kokkinos I., Murphy K., & Yuille A. (2018). *DeepLab: Semantic Image Segmentation with Deep Convolutional Nets, Atrous Convolution, and Fully Connected CRFs*. IEEE Trans. Pattern Anal. Mach. Intell., 40, 834–848.

Chizhova M., K. D. (2017). *Probabilistic reconstruction of 3d buildings using cellular automata*. International Archives of Photogrammetry, Remote Sensing, Spatial Information Science., 42, 187-194.

De Feo G. A. (2007). *Historical development of the Augustan aqueduct in Southern Italy: twenty centuries of works from Serino to Naples*. Water Science & Technology: Water Supply—WSTWS, 7(1), 131–138. doi:10.2166/ws.2007.01.

De FeoG. D. (2010). *The greatest water reservoirs in the ancient Roman world and the "Piscina Mirabilis" in Misenum*. Water Science & Technology: Water Supply—WSTWS, Vol. 10(3), 350-358.

He K., Gkioxari G., Dollár P., & Girshick R. (2020). *Mask R-CNN*. IEEE Trans. Pattern Anal. Mach. Intell., 42, 386–397.

Hou Y., Soibelman L., Volk R., & Chen M. (2019). *Factors affecting the performance of 3D thermal mapping for energy audits in a district by using infrared thermography (IRT) mounted on unmanned aircraft systems (UAS)*. Proceedings of the 36th International Symposium on Automation and Robotics in Construction, ISARC 2019, 266–273. <https://doi.org/10.22260/isarc2019/0036>.

Lin D., Jarzabek-Rychard M., Schneider D., & Maas H. G. (2018). *Thermal texture selection and correction for building facade inspection based on thermal radiant characteristics*. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives, 42(2), 585–591. <https://doi.org/10.5194/isprs-archives-XLII-2-585-2018>.

Lowe D. (2004). *Distinctive image features from scale-invariant keypoints*. International Journal of Computer Vision, 60(2), pp. 91–110.

Mayer Z., Heuer J., Volk R., & Schultmann F. (2021). *Aerial thermographic image-based assessment of thermal bridges using representative classifications and calculations*. Energies, 14(21). <https://doi.org/10.3390/en14217360>.

Wang Y. S. (2008). *Pictometry's proprietary airborne digital imaging system and its application in 3D city modelling*. The international archives of the photogrammetry, remote sensing and spatial information sciences., 37, 1065-1066.

Wong A., Famuori M., Shafiee M., Li F., Chwyl B., & Chung J. (2019). *YOLO Nano: A Highly Compact You Only Look Once Convolutional Neural Network for Object Detection*. arXiv Prepr.2019, arXiv:1910.01271, 1–5.