Urban Creativity Meets Engineering. Automated Graffiti Mapping along Vienna's Donaukanal

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Abstract. Graffiti are polarising. Some consider them vandalism, others part of our cultural heritage. If we consider graffiti to be part of our cultural heritage, we should also treat them as such. However, long-term and detailed graffiti documentation initiatives are sparse, so many of the existing archives with graffiti records are biased and incomplete. In addition, graffiti records usually suffer from decontextualisation, that is the lack of environmental information (be it spatially, temporally, but also smell and weather conditions). This means that graffiti documentation might not reflect the intended setting or meaning by the creator. INDIGO, a graffiti-centred academic project, largely overcomes the issue of decontextualisation by designing and implementing photogrammetric engineering approaches that support the ongoing documentation of an extensive graffiti-scape. The latter is situated along the Donaukanal, Vienna's central waterway and one of the most prominent graffiti hotspots worldwide. One innovation developed in the framework of INDIGO is a freely available Metashape add-on called AUTOGRAF. AUTOGRAF employs photogrammetric computer vision techniques to automatically create ortophotographs from all photographed graffiti. Orthophotographs or orthophotomaps are distortion-free images, combining photographs' visual qualities with characteristics of maps. They allow embedding the graffiti in their native, albeit virtual, 3D environment and can thus largely overcome decontextualisation.

In this contribution, we showcase the significant advantages of orthophotomaps over conventional photographs and introduce the AUTOGRAF-based workflow that allows the automated derivation of graffiti orthophotos. INDIGO will use this tailor-made tool to enable graffiti analysis in unprecedented detail by mapping and displaying graffiti in their original setting along the Donaukanal.

Keywords
AUTOGRAF; graffiti; orthophoto; photogrammetry; street art; structure from motion

1. Introduction

Even though ubiquitous, they are ephemeral, often disappearing within hours or days: graffiti. They accompany us through our everyday (urban) life. While some enjoy their omnipresence, others get annoyed or even feel provoked by the mere existence of painted (or smeared?) or scratched infrastructure. Beautiful or not? Artistic or not? Legitimate or not? Graffiti are polarising. This polarisation may be one reason for the increased attention received by graffiti, reflected in numerous magazines and newspapers featuring graffiti content (e.g., Peteranderl (2020) in Der Spiegel, Lohberger (2019) in Die Presse, Vandermerghel (2022) in

The Guardian, Gonzalez (2020) in The New York Times, and Saenz Gordon (2021) in The Red Bulletin). Since over a decade, graffiti have been increasingly entering mainstream media, and graffiti hotspots are often the most vibrant parts of cities. Today, guided graffiti tours are almost as common and popular as tours through established art museums.

Nevertheless, graffiti have not yet received the scientific attention they deserve (Masilamani, 2008; Ross et al., 2017). While 'ancient' graffiti (i.e. prehistoric cave paintings) are documented, preserved and analysed elaborately, the documentation and analysis of 'contemporary' graffiti often remain superficial and general. Ironically, this lack of scientific rigour is likely (partly) associated with the high frequency at which graffiti appear and vanish daily. The sheer amount of study objects and the ephemerality to which they are subjected complicate a continuous in-depth graffiti analysis.

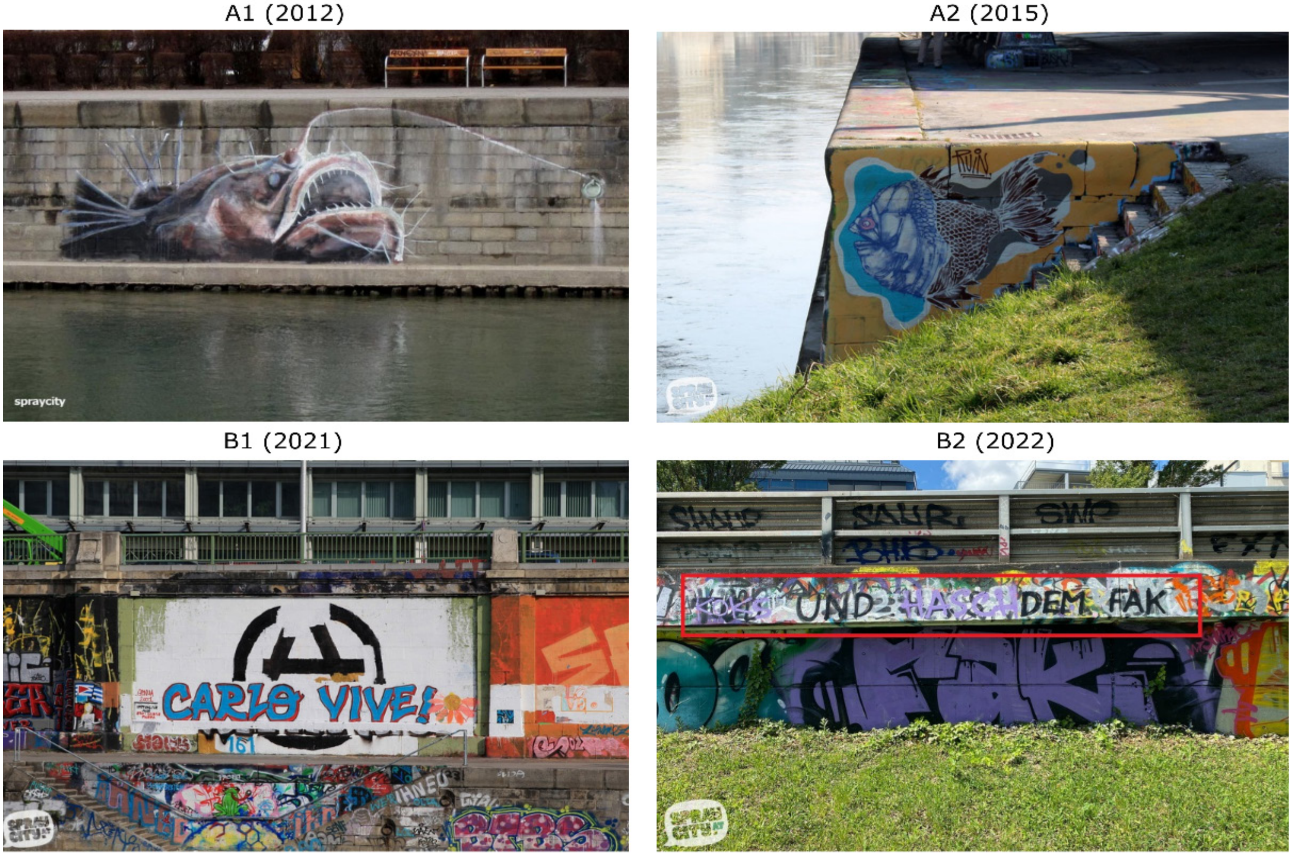
A1 (2012)
A2 (2015)
B1 (2021)
B2 (2022)

Figure 1. Example of graffiti records at the Donaukanal that are spatially pretty well contextualised. The images were downloaded from spraycity.at. The date in brackets denotes the year the graffito was first photographed. A1 and A2 show graffiti depicting fish-like creatures, a popular motive along the Donaukanal which habitats a surprisingly large fish population. B1 and B2 illustrate graffiti that affirm (B1) or manipulate (B2) the message of the graffito beneath. B1 references Carlo Giuliani, an Italian demonstrator whom a policeman shot during an anti-globalisation protest in 2001 in Genoa, Italy (McDonnell, 2007). It was sprayed on a circled A, a common symbol for Anarchism. B2 depicts a graffito devoted to the Viennese football club Austria Wien (abbreviation: FAK). The initial text above (highlighted in red) was "TOD UND HASS DEM FAK" (Eng: "Death and hate to the FAK") but was later manipulated to "KOKS UND HASCH DEM FAK" (Eng. "Coke and hash to the FAK").

There are initiatives dedicated to graffiti documentation. Projects like Global Street Art (http://globalstreetart.com), INGRID (https://www.uni-paderborn.de/forschungsprojekte/ingrid) and Spraycity (https://spraycity.at) provide well-curated and extensive graffiti databases. Graffiti photographs are the backbone of their documentation, often accompanied by metadata such as the creator's name, graffiti style or thematic content. Those metadata records are essential to analyse graffiti. However, they often miss one crucial aspect: the larger spatial context. For many graffiti, the content can only be understood in the environment they are placed in. 'Contextualised' graffiti is also discussed in various articles and essays (Bengtsen, 2014, 2019; Blanché, 2015; Ferrell & Weide, 2010; Riggle, 2010), highlighting the necessity to keep the spatial context in mind when documenting graffiti. Many works play with or manipulate the neighbouring environment, such as other graffiti, infrastructure or nature (Figure A1, A2). This location-specificity is also connected to temporality. The spatiotemporal context is relevant for graffiti referencing earlier works they are (partly or wholly) covering (Figure B1, B2). Sometimes those manipulations are identifiable, but in many cases, the reference remains hidden from the viewer due to the destruction of the work beneath. It can only be reconstructed by continuous (photo)documentation. However, even intensive photographic coverage sometimes does not suffice. The result of such documentation is usually a chronologically or thematically sorted collection of images, ideally spatially referenced by some coordinates, usually visualised as a dot on a map. This spatial simplification combined with the amount of collected photos often makes it hard to get the bigger picture. The works are presented as isolated entities and implicit but substantial parts of the work vanish, causing decontextualisation even in well-curated graffiti databases.

1.1. Project INDIGO and Vienna's Donaukanal

The academic graffiti-focused project INDIGO tackles, besides many other challenges, the issue of spatiotemporal decontextualisation by setting new standards in how graffiti are documented and disseminated (Verhoeven et al., 2022). INDIGO focuses its documentation efforts on one of the most prominent graffiti hotspots worldwide: the Viennese Donaukanal (Eng. Danube Canal). The Donaukanal is Vienna's central waterway and has a total length of 17 km. The 3.3 km long part of the Donaukanal on which INDIGO focuses features a combined stretch of approximately 13 km of graffiti-covered surfaces (Verhoeven et al., 2022), making it one of the longest uninterrupted graffiti zones globally. Not only is the mere spatial extent of Donaukanal's graffiti zone remarkable, but the pace at which new graffiti are created is exceptional. As the surfaces of Donaukanal are almost entirely graffiti-covered, creating a new graffito usually implicates the partial or complete destruction of one or several graffiti beneath (Figure 2). If not documented, the covered graffiti are lost forever, and with them, a socially relevant and fascinating part of our cultural heritage.

1.2. Textured 3D Geometry and 2D Orthophotographs

Of course, no documentation can ever replace the experience of viewing a graffito and appreciating it with all senses. However, modern techniques allow the accurate and digital construction of the real-world environment. 3D models enable us to place objects in their natural environment and thus provide the possibility to view and analyse them in their native, albeit digital, spatiotemporal context. Today, digital twins of (parts of) cities have become very popular because of the opportunities they provide and their relatively cheap and easy production (Dembski et al., 2020). Techniques such as laser scanning and image-based modelling are considered standard products in the digital construction of environments and are widely accessible (Brenner, 2005). INDIGO seizes these tools to allow researchers, graffiti creators, tourists and other interested users to gain an unprecedented realistic impression of the graffiti-scape along the Donaukanal.

These plans notwithstanding, the digital creation of an extensive and time-varying spatial 3D environment in which each graffito is queryable remains technically and logistically challenging. Large amounts of data must be acquired, stored, processed, interpreted and finally interactively disseminated. This volume covers many steps of this process. While the paper by Verhoeven et al. mainly focuses on photo acquisition, and the article by Molada-Tebar & Verhoeven presents the colour processing of the graffiti photographs, this contribution details the correct geolocation and geometrical correction of all photographs. These

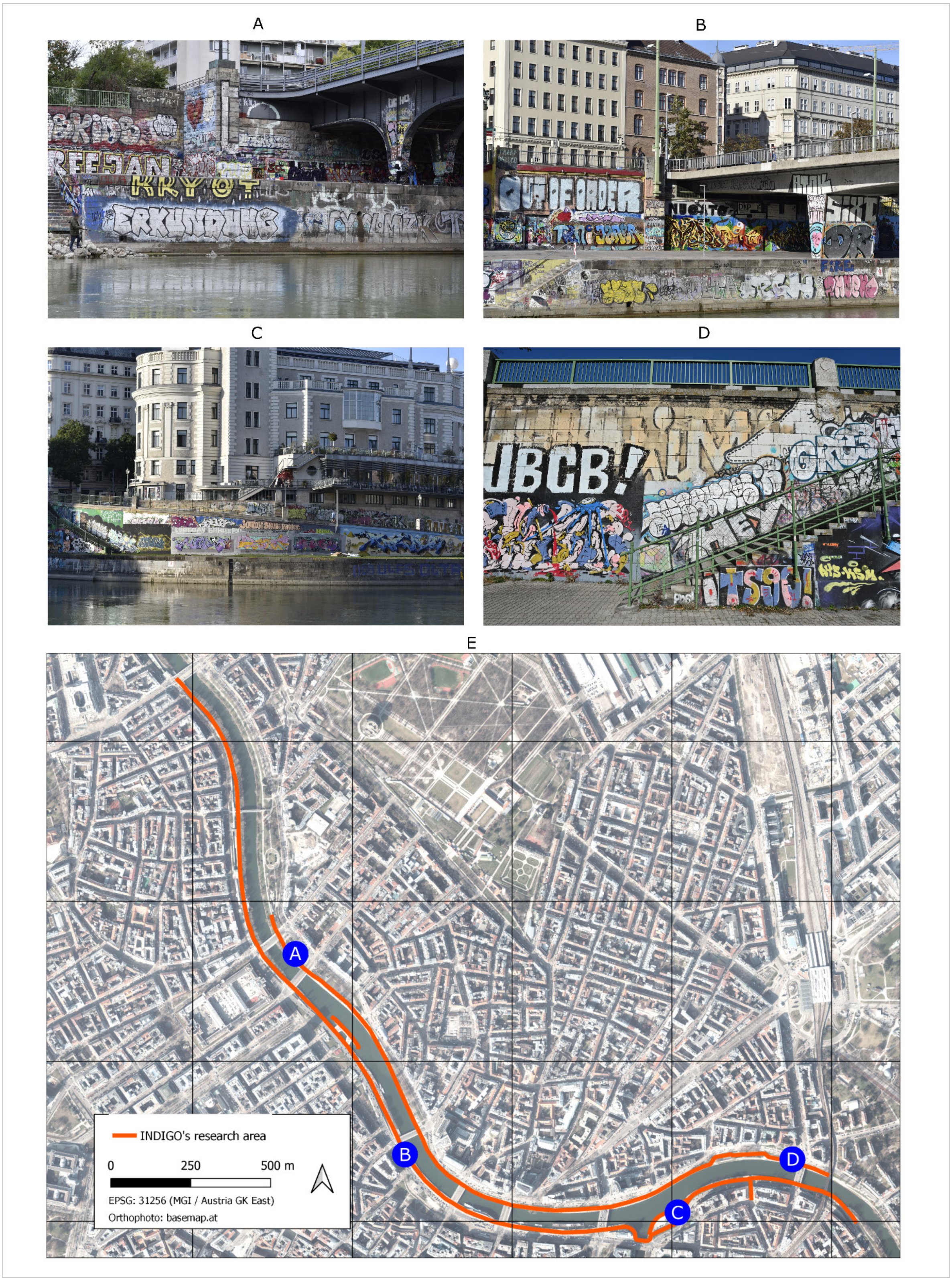

Figure 2. A-D: Example images of the graffiti-covered surfaces at the Donaukanal. E: Orthophoto of the Donaukanal with INDIGO's whole research area (dark orange) and the approximate locations of the graffiti depicted in A-D.

procedures are important because they will deliver the two main products for the envisioned online 3D platform.

The aim is to create an extensive, digital 3D model with colour-accurate textures of the Donaukanal's graffiti-scape. These textures, and the digital 3D geometry onto which they are applied, are both generated from the numerous graffiti photographs. However, the extraction of 3D geometry and texture mapping only works if the exact camera position is known. This paper will explain the process for obtaining this information and focus on an additional product that can be created once the camera position is known: an orthophoto. Section 2 details this concept, so it now suffices to know that an orthophoto represents a photo with map-like characteristics: it has a fixed scale, is devoid of geometrical distortions and enables the accurate measurement of a graffito's dimensions and proportions.

The combination of the 3D model with graffito-specific orthophotographs is INDIGO's answer to the decontextualisation issues mentioned above. The textured 3D model of INDIGO's envisioned online platform will allow users to view every graffito in its correct urban setting, both spatially and temporally. Suppose one also wants to study a graffito's dimensional, stylistic or semantic aspects. In that case, a highly detailed 2D orthophotograph can be viewed alongside the 3D model. Because the 3D textures and 2D orthophotographs will be queryable via an underlying database, the platform can support both intra- and inter-graffito visualisations and analyses, thus providing as much context as is currently technically feasible. Although urban smells and noises would make the contextualisation even more exhaustive, including these sensations is not planned.

The remaining part of the article will 1) focus on the geomatical techniques that support the accurate geolocation of every photograph, and 2) shed some more light on the orthophoto concept. However, we start with some examples to explain why orthophotos are indispensable products for documenting and disseminating graffiti.

2. Mapping Graffiti with Orthophotos

Orthophotos are no new invention, but they have helped humans understand and navigate the environment for many decades. We most frequently encounter them in aerial form, acquired from cameras mounted on satellites, aeroplanes or drones. These spaceborne or aerial orthophotos can be used like maps, but instead of abstracted shapes, they depict the natural situation. A significant difference between a conventional photo and an orthophoto is that the latter has a uniform scale allowing the measurement of correct proportions and dimensions of the depicted object. Orthophotos are thus also often referred to as orthophotomaps, enabling the accurate measurement of distances within a photo (Figure 3).

Figure 3. Example of a graffito orthophotomap with a uniform scale. Within this orthophoto, we can measure distances, angles and areas. The perimeter of this graffito is 36.82 m, and its area equals 51.2 m^2, making it one of the largest graffiti along the Donaukanal as of November 2021

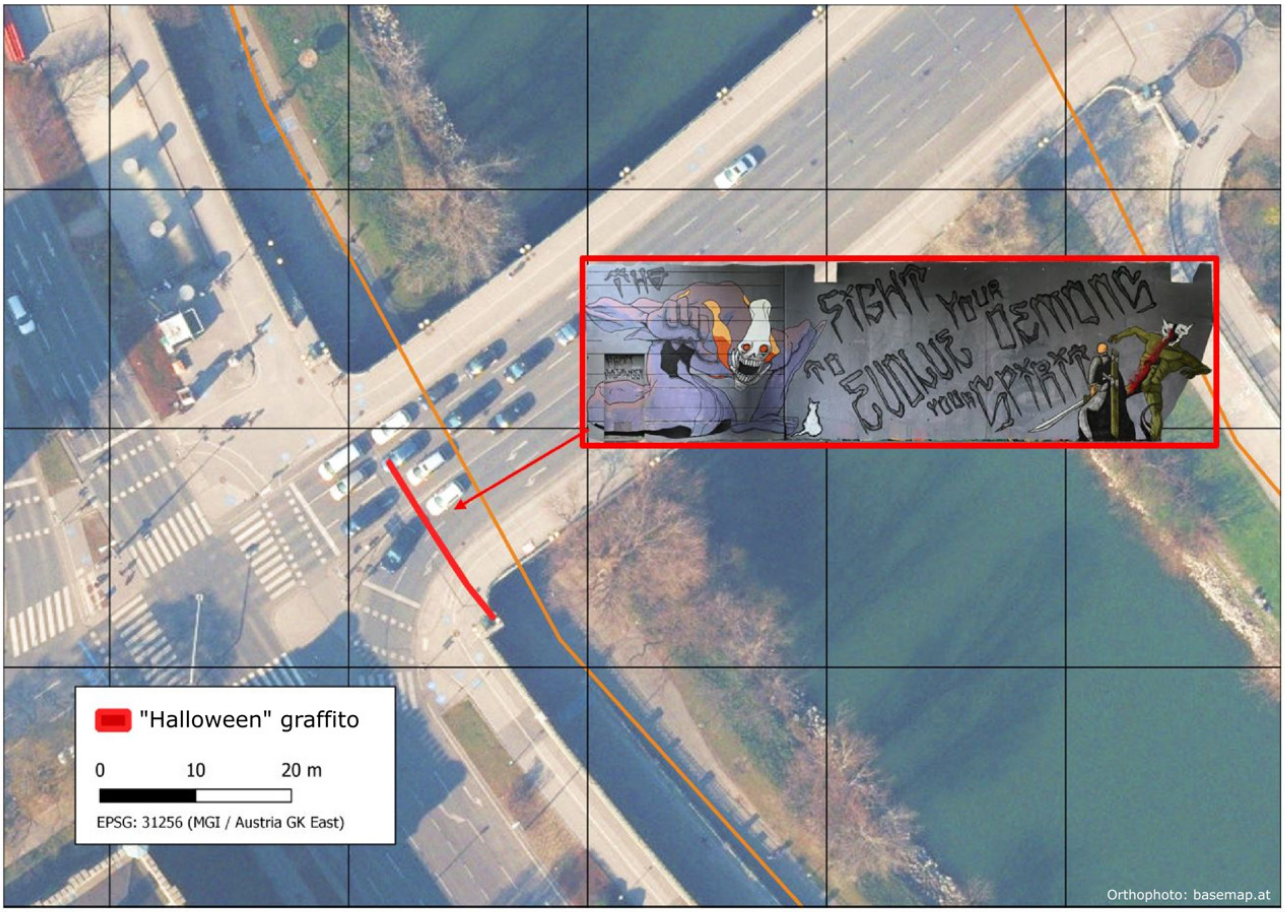

Figure 4. Aerial orthophoto of a small part of the Donaukanal showing the outline of the graffito (below the bridge) from Figure 3.

However, more information is hidden in orthophotos: they are usually georeferenced. Georeferencing implies that the absolute location of an object depicted in the image is known. For every pixel in the photo, a real-world coordinate can be assigned. With this information, one could go to the Donaukanal (virtually or physically) and see if the cat in the 'Halloween' graffito is still visible or has been oversprayed (Figure 4). Thus, orthophotos not only allow measuring within a photograph, they also connect the photo to the real world.

Single orthophotos can also be merged in a so-called orthophotomosaic, a very large composite orthophoto consisting of multiple individual ones that are seamlessly stitched together. Such mosaics support the study of extensive surfaces, while still providing much spatial detail (INDIGO' s orthophotos should depict, on average, details of about 2 mm). This technique supports even the distortionless depiction of extremely elongated graffiti. The next chapter will explain technical fundamentals concerning orthophotos and showcase how orthophotos are generated by introducing the orthophoto recipe.

2.1. The Orthophoto Recipe

Although sometimes hardly visible, every photo we take suffers from image distortions which are primarily caused by three factors:

- **Perspective distortions** occur when the object is not a single plane that is parallel to the focal plane of the camera (dashed red line, Figure 5).

Figure 5. Photograph taken around Halloween in November 2021. The photograph exhibits typical distortions occurring in conventional photos. The perspective distortion is highlighted with two converging dashed red lines. The orange rectangle shows an example of topographic displacement caused by a door in the wall. The lens distortion is made visible with the red dashed line. While the wall bottom is a straight line in the real world, its image is slightly curved.

- **Topographic distortions** are caused by the topographic relief of the photographed object (i.e., the graffito-carrying surface). Since an orthophotograph mimics the observation of a surface with a viewing direction orthogonal to the graffiti plane, it does not make clear if elements are intruding or extruding. In Figure 5 (see orange rectangle) the right and lower part of the intruding door frame are, however, visible in the photo. Another good example is an aerial orthophoto of a city with a large tower. The top and foot of the tower should be in the same position when viewed orthogonally from above, but the side of the building will likely be visible in the aerial image due to the central perspective of the camera. That is why elements lying below or above a horizontal reference surface (like the tower in the aerial image or the door which lies deeper than the overall vertical reference surface) are said to be topographically misplaced. The further such elements are located from the reference surface, the larger their topographic displacement or distortion will be.
- **Lens distortions** are caused by unavoidable imperfections in the mechanical realisation of the camera's lens system. They are usually manifested to the viewer by the inward or outward bowing of straight lines when lenses with very small or rather large focal lengths are used. Compared to the distortion types above, lens distortions usually play a subordinate role. However, they are still visible (e.g. in Figure 5), so they should be accounted for.

Together, these distortions cause the object in a photo to appear warped, sometimes occluded and without a uniform scale. Figure 5 demonstrates the issues with a conventional

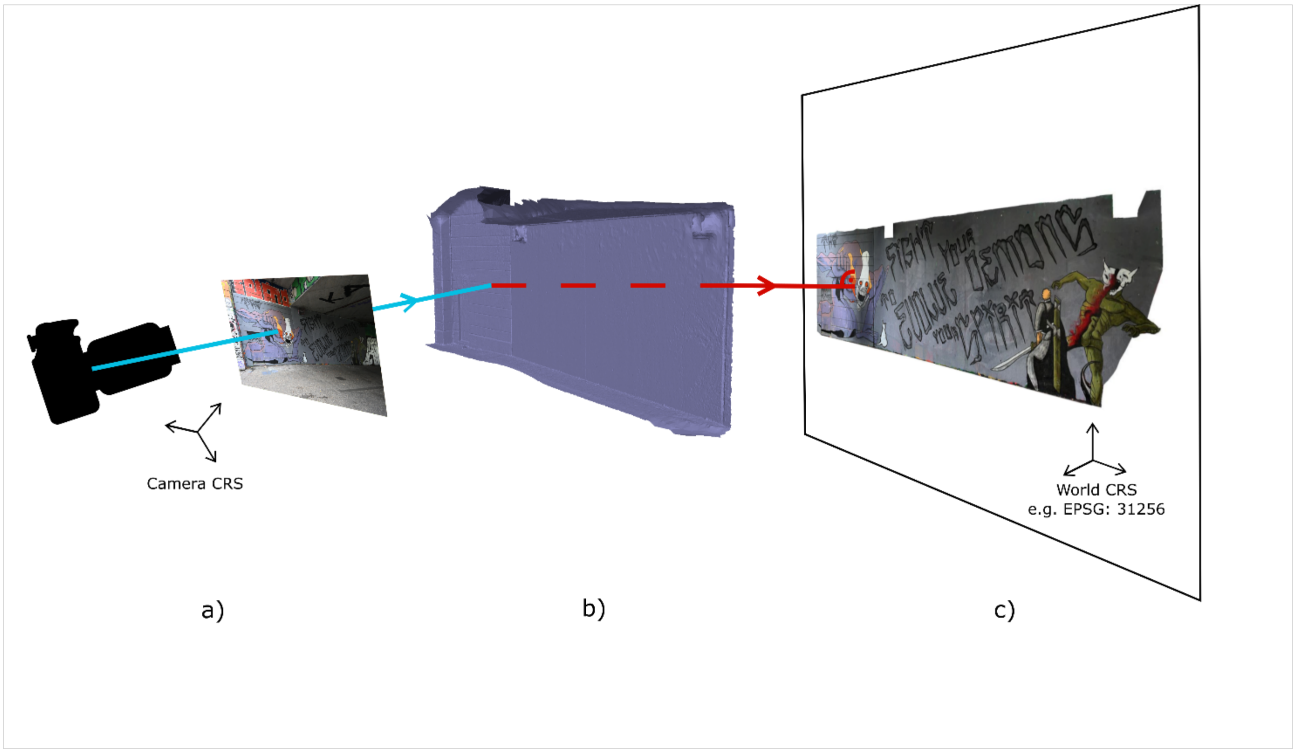

Figure 6. Schematic depiction of the orthorectification process with all 'ingredients' to the orthophoto recipe (Wild et al., 2022).

graffito photograph. One could dampen the effects of perspective distortion by changing the acquisition angle and position. However, changing the shooting direction can never account for all distortions and is often impossible due to photographic constraints at the scene. In the case of INDIGO, many graffiti are close to the water or on bridge pillars. These can only be photographed obliquely, causing significant perspective distortions.

We can remove all three types of distortion and simultaneously scale the photo by applying the orthophoto recipe (Figure 6). The technical term for this process is orthorectification, and its 'ingredients' are:

a. The interior and exterior orientation parameters of the camera used; the camera's interior orientation mathematically describes the internal camera geometry, including lens distortion parameters. The exterior orientation describes the position and angular rotation of the camera when acquiring the photo.
b. A digital 3D model of the graffiti-covered surface (i.e. the wall, bridge pillar, staircase).
c. A projection plane (i.e. the reference surface mentioned before) serves as the canvas for the final orthophoto.

Knowing the camera's orientation is necessary to compute the direction vector (green ray in Figure 6), which is intersected with the 3D model of the scene (which takes care of the topographical distortions). The pixel values are then orthogonally projected (red ray) onto the projection plane to also remove the tilt distortion. In this manner, the photograph can be orthorectified pixel per pixel. Because we know the exact geospatial position of the camera (given by the exterior orientation), the final orthophotograph is also correctly georeferenced.

2.2. Automating the Graffiti Orthorectification

While the orthorectification principle is relatively simple, the difficulty lies in retrieving all the required data. Besides being reliable, this step needs to be highly automated considering the large number of graffiti photos project INDIGO generates each week. Fully automated orthorectification without human intervention is the innovation we present in this section.

INDIGO's bespoke orthorectification tool AUTOGRAF (AUTomatic Orthorectification of GRAFiti photos) takes several photos of one graffito as input, derives all necessary orthorectification parameters and outputs the georeferenced orthophoto. Since every graffito is covered by multiple photos, the final product can be considered an orthophotomosaic. AUTOGRAF is developed as an add-on to the commercial software Metashape Professional by Agisoft LLC (Agisoft LLC, 2022), which already provides many functionalities necessary for orthorectification. Explaining the tool and its capabilities in detail would go beyond the scope of this contribution. Instead, we give a brief and straightforward overview of how the INDIGO tool automatically generates accurately georeferenced orthophotomosaics from thousands of photos that capture the hundreds of graffiti monthly appearing on the urban surfaces along the Donaukanal. For more details on AUTOGRAF, the reader is referred to Wild *et al.* (2022). At https://github.com/GraffitiProjectINDIGO/AUTOGRAF, the tool can be downloaded freely.

The INDIGO orthorectification happens in three steps (Figure 7): 1) initial quality checks of the inputted graffiti images, 2) the automated retrieval of the (interior and exterior) orientation of the cameras at the moment of the respective image acquisition, and 3) the derivation of the 3D surface model and the projection plane. These three steps are followed by the orthophoto computation.

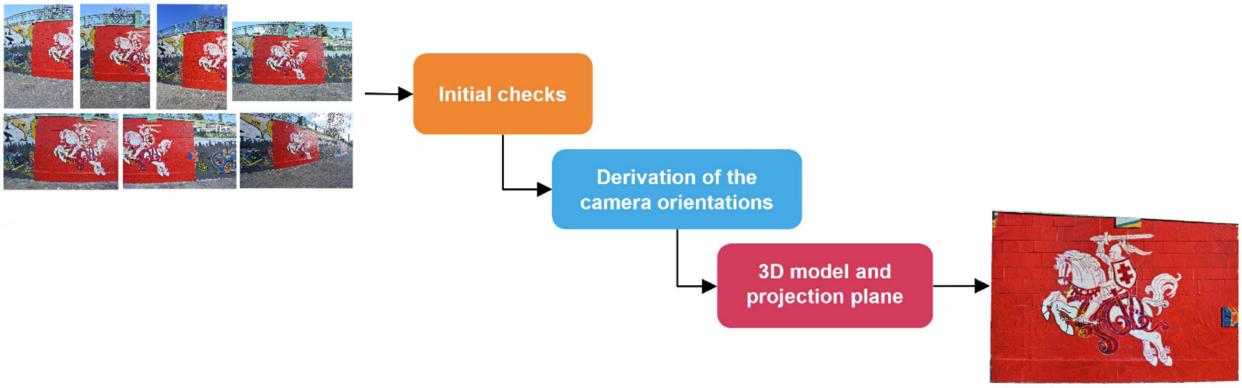

Figure 7. Simplified flowchart of INDIGO's automated orthorectification pipeline.

After AUTOGRAF receives photos of one graffito, the initial checks validate their consistency and quality. Blurry images or images erroneously assigned to a certain graffito are automatically identified and discarded in further processing. This prior image filtering not only improves the reliability of the workflow but also reduces the processing times, which is a crucial advantage considering the thousands of images INDIGO acquires every month.

For all photos that pass the initial checks (usually around ten per graffito), the camera orientations are computed by identifying common feature points between image pairs, a technique commonly referred to as image matching. These feature points 'tie' the images together, which subsequently allows an algorithm like structure from motion (Ullman, 1979) to retrieve their interior and relative exterior orientations. To recover the exterior orientation parameters, including the camera's exact location and 3D tilt at image acquisition, tie points are then sought between this network of approximately ten graffito-specific images and an existing network of circa 27 000 oriented photos that cover INDIGO's entire research area. The INDIGO team acquired these images in the autumn of 2021 (see Verhoeven et al. in this volume), and their exterior orientations were retrieved and expressed in the Austrian coordinate reference system MGI / Austria GK East (EPSG:31256). With this 'total-coverage photo network', it is possible to continuously and incrementally add new images while simultaneously retrieving their interior and exterior camera orientations (Figure 8). In this way, INDIGO's entire photo network grows with about ten images when a new graffito gets geometrically processed. Figure 8 also shows that all the image tie points can be visualised as a 3D point cloud.

Once all photographs of the graffito are oriented, the 3D surface model can be extracted by so-called dense multi-view stereo matching (Seitz et al., 2006), which results in a much denser point cloud. By connecting these points into

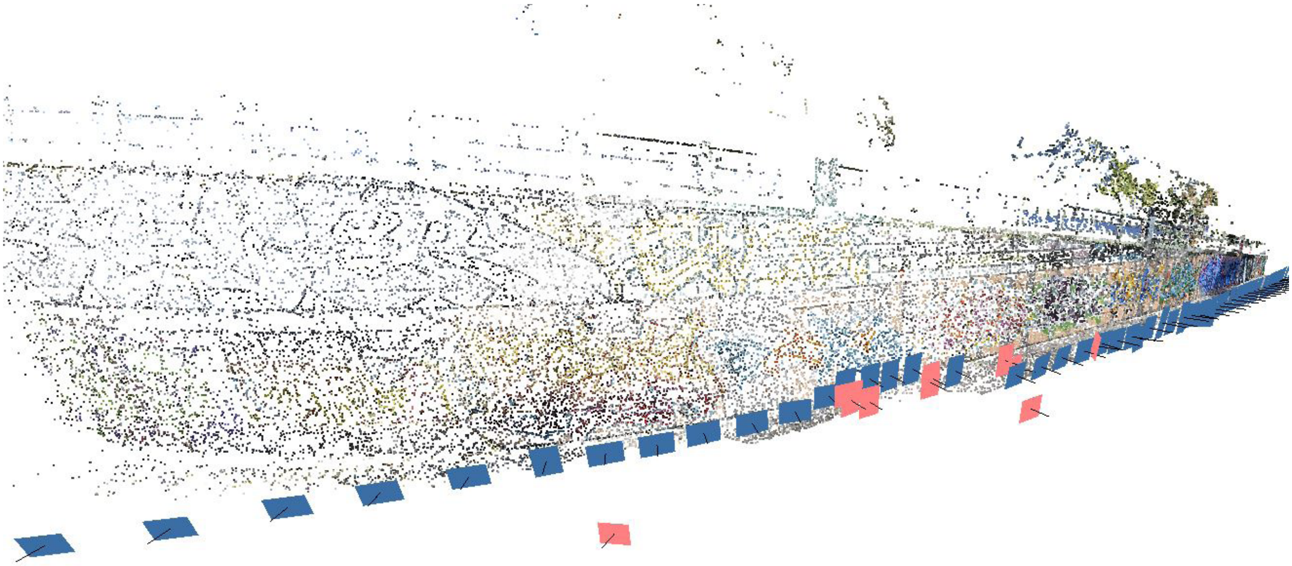

Figure 8. Depiction of a tie point cloud, including the oriented cameras symbolised as blue and pink rectangles. Blue rectangles denote already oriented images (i.e. the existing network of oriented images at that stage). Pink rectangles denote the incrementally added photos of a new graffito.

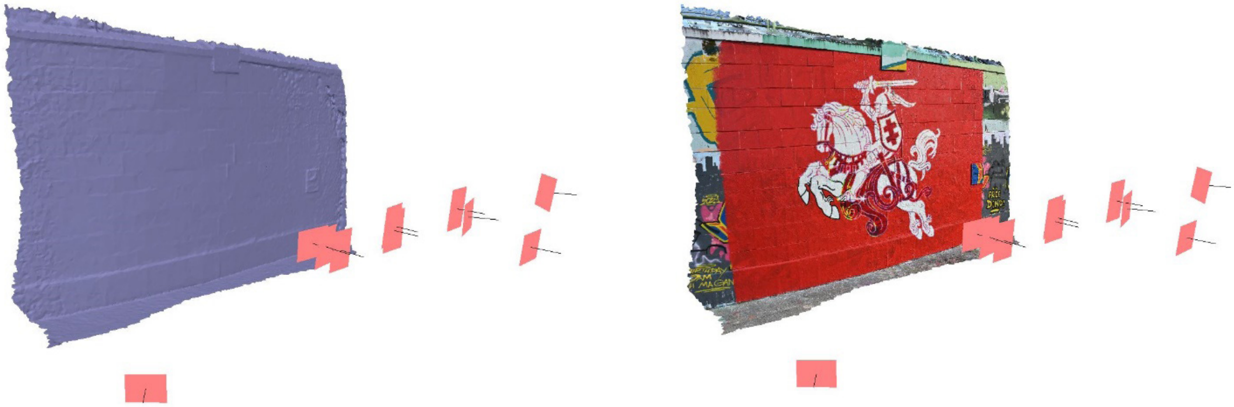

Figure 9. 3D meshed surface model (non-textured: left; textured: right) of an exemplary graffito scene. Red rectangles symbolise the locations and tilts of the camera sensor for the various photographs.

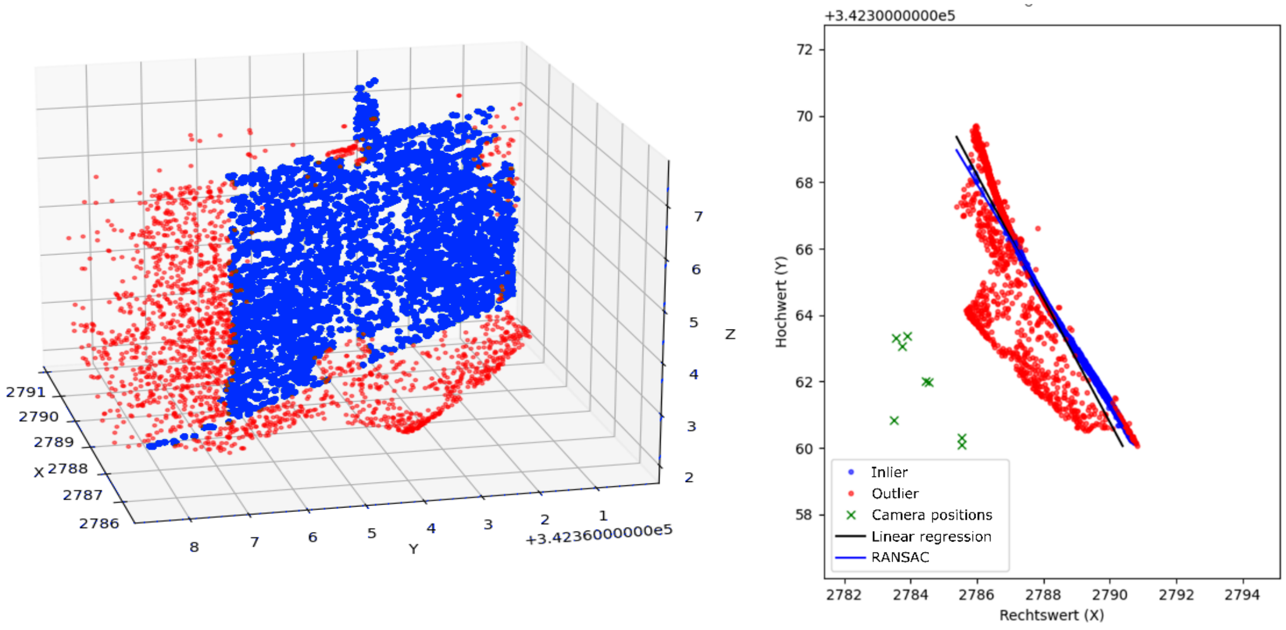

Figure 10. RANSAC-classified tie point cloud. Blue dots denote points belonging to the graffiti-covered surface. Red dots denote outliers not part of this surface.

triangles, a continuous so-called triangular meshed 3D surface is derived (Figure 9 on the left). Finally, the images can also be projected onto this 3D meshed surface to generate a photographic texture for it (Figure 9 on the right).

Although the 3D meshed surface and its texture are products that will go into the online 3D platform, no orthophotomosaic has been computed at this stage. To that end, we first need to define the reference surface or projection plane. This projection plane is computed by fitting a plane into the tie point cloud. As this 3D point cloud also contains points that do not belong to the graffito-covered surface (e.g., trees or facades in the background), the point cloud is filtered (Figure 10) using the outlier detection algorithm RANSAC (RANdom SAmple Consensus; Fischler & Bolles, 1981). The result is a plane approximating the surface onto which the graffito was created. This method fails only for graffiti generated on highly complex surfaces (e.g., bridge pillars or staircases), which means that manual intervention is necessary if proper orthophotomosaics are needed from these surfaces.

This automated process results in a detailed orthophoto of the graffito (on average a raster cell of circa 0.9 mm, effectuating a spatial resolution of about 2 mm), thus supporting detailed mapping and dimensional or contentual analyses. Because the orthoimage also includes accurate geolocation info, it can be correctly positioned in the usual 2D maps (see Figure 11) but also in a digital 3D environment.

2.3 The 100-Graffiti Experiment

AUTOGRAF was applied to 100 randomly selected Donaukanal graffiti created between November and December 2021. The graffiti were documented with 826 photographs, which were separated into individual folders and fed into the software. This experiment was conducted on a PC with the following relevant specifications:

Figure 11. Orthophoto example (left) with the corresponding location of the graffito along the Donaukanal (right, orange line).

- CPU: Intel Core i9-12900KF, 3.2 GHz, 16-core processor
- GPU: NVIDIA GeForce RTX 3060, 12 GB DDR6 VRAM, 3584 CUDA cores
- HDD: Seagate FireCuda 530 2TB M.2 SSD, 7300 MB/s read, 6900 MB/s write

RAM: 64 GB DDR4-4400, 2200 MHz Overall, the tests yielded very promising results. Only five graffiti could not or only very poorly be orthorectified. In return, 95% of the graffiti were accurately georeferenced and satisfyingly orthorectified. Displaying the graffiti orthophotomosaics on a 2D map emphasises the reliability of the developed workflow and shows how equally the spraying activity is distributed along the Donaukanal (Figure 12)

Besides the tool's reliability, its computational demand is of vital interest considering the large amounts of photographs that will be processed during the INDIGO project. Overall, it took 10 hours and 33 minutes to process the 826 images and turn them into graffiti orthophotomaps. The average processing time per graffito was 6 minutes and 20 seconds, indicating that at least AUTOGRAF will be able to keep up with the enormous speed at which graffiti are created and documented at the Donaukanal.

3. Outlook and Conclusion

In this contribution, we explained the orthophoto concept, highlighted its importance in digitally preserving and analysing graffiti, and introduced a freely available tool that supports the automated derivation of orthophotos from thousands of graffiti photos in the context of project INDIGO. The introduced tool does not only remove image distortions from the graffiti photographs, but also puts the digital graffiti record in the right geographical spot. With these data, one can reconstruct the different layers of a graffiti-covered wall and see what was beside, above or below a given graffito. Knowing a graffito's location also supports questions like 'Where are the graffiti hotspots?', and by linking this geographical orthophoto information with additional metadata even more complete analysis of the graffiti-scape can be conducted. The question of 'Where are hotspots of…' can, for example, be specified with keywords like 'political graffiti' or 'graffiti of artist XY'.

One of INDIGO's central aims is a 3D + 2D platform allowing neat visualisation of graffiti in their native environment. This platform is still being developed, and many technical hurdles like efficient data streaming of enormous datasets are still to be solved. However, our proposed methodology sets the basis to overcome a major obstacle in today's graffiti documentation and analysis, thereby directly tackling

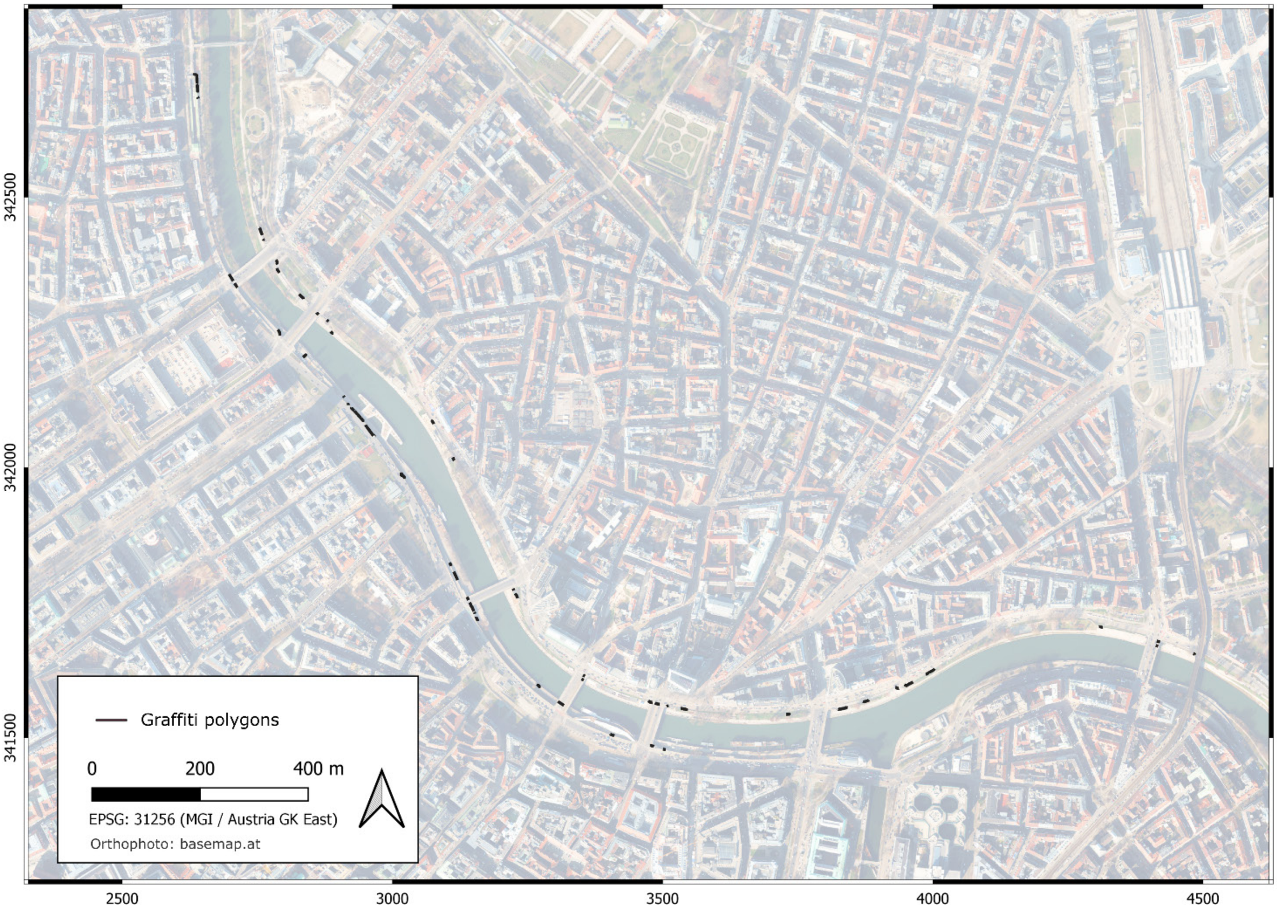

Figure 12. The outlines of the 95 successfully orthorectified graffiti photo sets. The base map was made transparent to improve visibility.

the issue of graffiti decontextualisation. All this will hopefully contribute to novel ways of experiencing and scientifically analysing graffiti-scapes, in turn boosting the understanding and heritagisation of these colourful and diverse mark-making practices.

Conflict of Interests

The authors declare no conflict of interests.

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