DIGITAL HERITAGE (2025)
S. Campana, D. Ferdani, H. Graf, G. Guidi, Z. Hegarty, S. Pescarin, and F. Remondino (Editors)

Acquisition and digitization of large-scale heritage scenes with open source project https://github.com/MapsHD/HDMapping

J. Bedkowski [1] and M. Matecki [1] and M. Pelka [2] and K. Majek [3] and T. Fitri [4] and A. Kostrzewa [5]

[1] Institute of Fundamental Technological Research, Polish Academy of Sciences, Poland
[2] robotec.ai, Poland
[3] Cufix, Poland
[4] Mandala, Poland
[5] Warsaw University of Technology, Faculty of Geodesy and Cartography, Department of Photogrammetry, Remote Sensing and Spatial Information Systems, Plac Politechniki 1, 00-661 Warsaw, Poland

Abstract

This paper describes an open source project https://github.com/MapsHD/HDMapping for large-scale 3D mapping using an open-hardware hand-held LiDAR measurement device available at https://github.com/JanuszBedkowski/mandeye_controller in application of large-scale heritage scenes acquisition and digitization. It implements multi view terrestrial laser scanning algorithms, LiDAR odometry, Pose Graph SLAM (Simultaneous Localisation and Mapping), NDT (Normal Distributions Transform) and ICP (Iterative Closest Point). Mobile mapping systems is based on LiVOX MID360 - laser scanner with non repetitive scanning pattern equipped with equirectangular camera. This project runs from 2023, the current version v0.76 has significant improvements in lidar odometry and georeferencing. The goal of the project is to provide an affordable mobile mapping system and an open source software that can be widely used also by Culture Heritage community.

CCS Concepts

• ***Computing methodologies*** → *LiDAR odometry, ICP, NDT, Pose GRAPH SLAM;* • ***Hardware*** → *LiDAR LiVOX MID360, camera Insta360 X4;*

1. Introduction

Digitalisation of Cultural Heritage in the Perspective of War and Conflict Culture and its heritage is part of human's tacit knowledge manifested and or materialised through tangible symbols, artefacts and architecture are crucial elements in maintaining identities, cultural memories, know-how, knowledge and science of a given culture and traditions as part of a nation's anthropological wealth. The destruction of any of these tangible elements may contribute to the loss of societal intangible culture and traditions which corresponds to the changing nature of the societal way of seeing and thinking. Hence, the interconnectedness between tangible heritage and the intangible aspects of heritage will have to be considered as non-negotiable for the well-being of a given culture, tradition and society. A threat to one's culture and tradition, is a threat to other cultures and traditions, since tradition and culture function as a home for any individual who adopts, understands and accepts the intangible aspects, the symbolism, and the meaning of the given culture and tradition. Hence, any threat to its existence, both tangibly and intangibly, will naturally be considered a serious threat to humanity at large due to its psychosocial impact. Society in general will respond to any destruction of the tangible structure of cultural heritage with anger, disappointment or despair. Other than acts of terrorism and natural disasters, war and armed conflicts are notorious for their ability to destroy a cultural heritage site, whether targeted or not. The UNESCO's Hague Convention in 1954 for the Protection of Cultural Property in the Events of Arm Conflicts the proof of how significant is the impact of cultural heritage destruction by World War II. As an example, Poland and her capital experienced massive destruction. Its restoration somehow changes the nature of the city from pre-World War II. Whether or not a restoration of a cultural heritage should carry its exact collective memories of the previous values, symbols, and layout, any restoration will require comprehensive efforts. Technological approach and contribution will be crucial for assisting the process from prevention to restoration. Our system is aimed at providing an affordable solution for the management of large cultural heritage sites' digitalisation for a wide range of purposes. Hence, it supports UNESCO's aims in Civil-Military Alliance for the Protection of Cultural Property.

Mobile mapping systems [KNP*25] have been widely used in Culture Heritage surveys for a long time [MRR05]. It can take photos with external orientation parameters thanks to GPS and INS. The hand-held mobile mapping system Zebedee applied for Culture Heritage was introduced at [ZBJ*12] and an extended elaboration of this research was elaborated in [ZBG*14]. The authors

DOI: 10.2312/dh.20253026

were focused on technology enabling measurements in geometrically complex locations to be acquired from a variety of viewpoints. The claim is that while several technologies exist for capturing the 3D structure of objects and environments, none are ideally suited to complex, large-scale sites, mainly due to their limited coverage or acquisition efficiency. Hand-held mobile mapping systems are more popular [ALGLB*23] [MMS*21] since they are more and more affordable compared with Terrestrial Laser Scanning [TWS14] [CNX*20] [DLY*20]. A comparison between terrestrial laser scanning and hand-held mobile mapping system for documentation of built heritage [CPBT24] shows the importance of evaluating different methodologies based on project objectives and desired levels of detail, providing insights into the strengths and limitations of each system for diverse applications in heritage documentation. A new trend in mobile mapping systems' development shows an interest in wearable solutions [ALGLB*23], [LBH*15]. High mobility with a mobile mapping system (climbing and crawling) was elaborated in [BF24]. In this work [EAQ22] Authors elaborated different mobile mapping systems including a vehicle-mounted mobile mapping platform, handheld, wearable systems and trolley-based mobile mapping system. An interesting application of mobile mapping survey for structural analysis of historical constructions was elaborated in [SAMC*21]. This work shows several advantages, such as the great performance or the flexibility of it. The authors observed that the time invested in digitalizing the church was reduced by about 7.5 times compared to traditional techniques. The portability makes it possible to digitalize complex and narrow spaces. Unfortunately, the data provided shows noise which hinders the creation of a CAD model and requires the use of noise reduction filters.

To organize mobile mapping systems applied in Culture Heritage we provide a taxonomy in figure 1. We distinguish two dimensions in the proposed taxonomy. First, there are indoor and outdoor tasks. In the outdoor scenario, we have access to GPS signals, thus mobile mapping systems can benefit from PPP/RTK services providing centimetre level accuracy [BNK*21]. In indoor surveys, we should apply SLAM with georeference techniques to reach satisfactory accuracy [Bed22]. Looking at the scope of the survey we distinguish large, middle, small and mini scales.

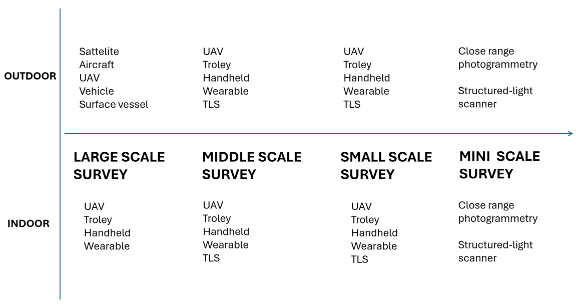

Figure 1: *Taxonomy of mobile mapping systems applied in Culture Heritage.*

1.1. Outdoor large scale survey

Outdoor large-scale surveys (e.g. continent [BNK*21], country, city, island) require covering scope with multiple sessions (session is single data collection, e.g. single trajectory). Each session can be easily georeferenced with GPS e.g. with our software [Bed24]. Starting from inaccessible heritage sites we can assess them with satellite imagery [MRD*21]. Generally, airborne and spaceborne remote sensing [LWG*19] is a non-destructive tool, that is increasingly popular by specialists around the world as it allows fast prospecting and mapping at multiple scales, rapid analysis of multisource datasets, and dynamic monitoring of ACH (Archaeological and Cultural Heritage) sites and their neighbouring environments. Unmanned Aerial Vehicles are also efficient tools for the collection of archaeological and cultural landscape data [The20] [Ulv20]. UAVs can be equipped with high-resolution cameras and/or LiDARs [SSAF*19] [NR14]. For outdoor accessible land surveys, we can use vehicles equipped with mobile mapping systems [PGJMSA13] [YJW*24]. Last but not least is the mobile mapping system mounted on surface vessel [MTT*17] [TS24] [TS] [CSVB24]. It is worth mentioning underwater vessels [TSFS0] that can be also used, but in our opinion, it is difficult to classify them within the proposed taxonomy.

1.2. Indoor large scale survey

Indoor large-scale survey (e.g. entire buildings) requires covering scope with multiple sessions. There is limited access to GPS. Indoor large-scale survey [OBAV21] requires a hybrid approach of mobile mapping and TLS to reach satisfactory scope, accuracy and local precision. It covers entire buildings, top, bottom and underground levels [Bed24] [MT24] [TKWR23]. Underground mines mobile mapping technology [ZB14] can be applied here. Due to the large scope of the survey the trolley [OLGA20] and wearable solutions [KVP*19] are applied to minimise fatigue. The challenge is to reach satisfactory accuracy since georeferencing is not always feasible.

1.3. Outdoor middle scale survey

Outdoor middle-scale surveys (e.g. streets with buildings) can be covered by a single session. It means we can provide results based on data collected on a single run. It sufficiently simplifies the data management and processing pipeline compared with large-scale surveys. In most cases we do not need a powerful data center [BNK*21], thus all calculations can be done on a single computer. Several modalities such as UAV, trolley, hand-held, wearable and TLS can be used separately or resulting data can be fused and georeferenced e.g. by our software [Bed24].

1.4. Indoor middle scale survey

Indoor middle-scale surveys (e.g. single level of the building) can be covered by a single session. It is a typical scenario known in mobile robotcs [AFDT22] [LAH*25] [BHH*15] since early research in SLAM (Simultaneous Localisation and Mapping) that was undertaken by Leonard and Durrant-Whyte in the early 1990s [LDW91]. Most recent modalities such as indoor UAV [KNCK22]

[LRS*23] [HKT22], trolley, hand-held, wearable and TLS can do this job efficiently.

1.5. Outdoor small scale survey

The outdoor small-scale survey (e.g. single building) is covered by a single session. This type of survey results in a model of a single building. To reach full coverage the combination of UAV with ground mobile mapping system (e.g. trolley, handheld, wearable, TLS) can be incorporated [GFHS25] [WHP*23].

1.6. Indoor small scale survey

The indoor small-scale survey (e.g. single room) is covered by a single session. As in most previous cases UAV, trolley, handheld, wearable and TLS can be used. This survey is rather straightforward since we perform scans typically inside single rooms without complex corridors [MKMea23].

1.7. Outdoor mini scale survey

The goal of the outdoor mini-scale survey is to provide high-resolution data [MVI*22] that can be obtained with close-range photogrammetry [YYGD07] [AHLO05] [REH06]. It is common to fuse different 3D modalities [Rem11] [GRE*09] [Yas07] to reach high resolution locally and large coverage globally. An interesting project a self-assembly portable mobile mapping system for archaeological reconstruction based on the VSLAM-Photogrammetric algorithm is elaborated in [OCSR19] and it is evidence that an affordable solution can provide satisfactory data.

1.8. Indoor mini scale survey

Close-range photogrammetry technique [Luh10] is typically used in indoor mini-scale surveys for small objects' [PST00] [KAS*13] digitisation. An alternative technique is structure light [XWL*20], handheld 3D laser scanner (HLS) and high-resolution handheld digital microscope (HDM) [SNRBB25] as complementary tools for TLS measurements. A brief survey of the hardware setup, algorithms and software tools for photogrammetric acquisition and reconstruction applied to small objects is elaborated in [DPDLG*20].

1.9. Our contribution

Based on the above elaborated literature we can observe the fact that the scope of culture heritage surveys is already covered by plenty of modalities. The challenge is to reduce the cost of a 3D mapping system, thus more culture heritage sites can be digitised, thus preserved data can be stored for further analyses. For this purpose, we designed a mobile mapping system that is improved over time. It is available at https://github.com/JanuszBedkowski/mandeye_controller. We provide also an open-source project https://github.com/MapsHD/HDMapping that can process surveys composed of multiple sessions. In this paper, we show several culture heritage large-scale surveys. All experiments are replicable thanks to the open-source open-harware approach.

2. Affordable mobile mapping system

Figure 2 shows our open-hardware DIY (Do-it-yourself) mobile mapping system. It is composed of non-repetetive scanning pattern LiDAR LiVOX MID360 https://www.livoxtech.com/mid-360 (the laboratory tests of metrological characteristics can be found here [MKG24]), 360 camera Insta360 X4 8K (8K, 30fps), GNSS receiver (currently ublox n8m but it will be replaced with ublox X20 in near future), synchronisation ring (custom camera to LiDAR synchronisation based on LEDs showing timestamp with Gray code, an open-source project is available at https://github.com/MapsHD/MandeyeLedTimestamp). Camera to LiDAR post-process synchronization is done with 100ms resolution. LiDAR provides 200.000 points per second with 2cm accuracy on 20m. We strongly believe that our solution is the most affordable one in its class - this is our main contribution to the research community. The novelty of our approach is the fact that we collect all images (8K, 30fps) and point clouds that can be synchronized in post-process. It opens new research directions that will be elaborated in section 6.

3. Culture Heritage surveys

In this section, we demonstrate the usability of the proposed mobile mapping system for data acquisition and digitization of large-scale heritage scenes with our open hardware https://github.com/JanuszBedkowski/mandeye_controller and open source https://github.com/MapsHD/HDMapping. We show the results of the five surveys in Italy (Siena, Chiusdino, Roccastrada, San Gusme). We show how to fuse aerial LiDAR data with hand-held mobile mapping data based on an example of facade mapping of the Palace of Culture and Science, Warsaw, Poland. Finally, we show the colour point cloud of the other facade.

3.1. Siena, Italy

This survey can be categorised as an outdoor large-scale survey since it is composed of more than 10 sessions of a total length of more than 100km. Data was collected in Siena, Italy 14 consecutive days from 6 up to 8 o'clock in an average speed of 4km/h. The results are shown in figures 4,5,6.

3.2. Chiusdino, Italy

This survey can be categorised as an outdoor middle-scale survey since it is composed of a single session. Results are shown in figure 7.

3.3. Pisa, Italy

This survey can be categorised as an outdoor middle-scale survey since it is composed of a single session. It is challenging since plenty of tourists affect 3D measurements. Results are shown in figures 8,9.

Figure 2: *Affordable mobile mapping system - front view.*

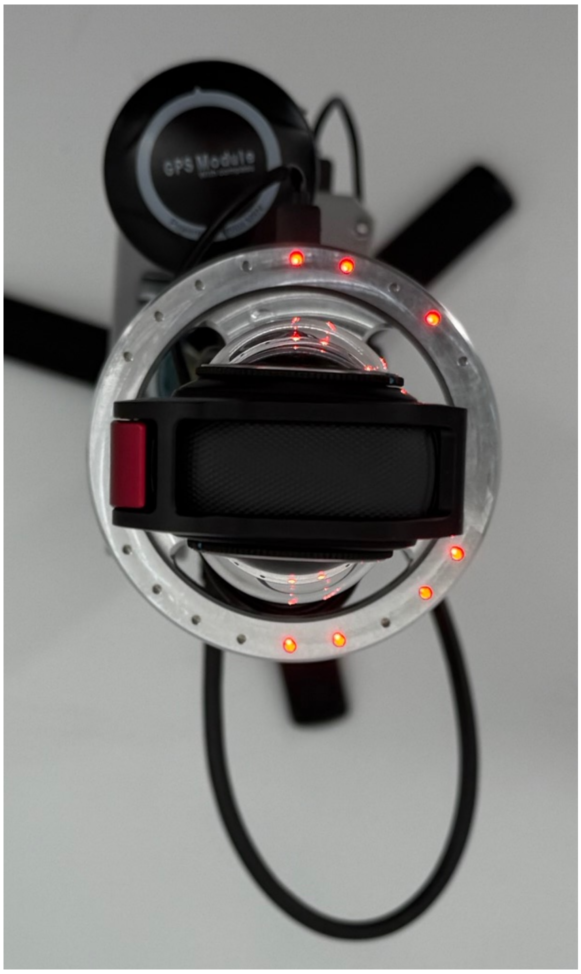

Figure 3: *Affordable mobile mapping system - top view. Custom camera to LiDAR synchronisation based on leds showing timestamp with Gray code, an open-source can be found at https://github.com/MapsHD/MandeyeLedTimestamp.*

Figure 4: *Siena, Italy: survey photos.*

3.4. Roccastrada, Italy

This survey can be categorised also as an outdoor middle-scale survey since it is composed of a single session. It is challenging since plenty of tourists affect 3D measurements and narrow spaces. Results are shown in figures 10,11,12.

3.5. San Gusme, Italy

Similarly to the previous one, this survey can be categirised also as outdoor middle-scale survey since it is composed of a single session. Results are shown in figures 13,14,12.

3.6. Palace of Culture and Science, Warsaw, Poland

This survey can be categorised also as a combination of outdoor large scale survey and outdoor middle scale survey since it fuses aerial LiDAR data (figure /reffig:pk1) available at https://www.gov.pl/web/gugik/dane-udostepniane-bez-platnie-do-pobrania-z-serwisu-wwwgeoportalgovpl with our hand-held mobile mapping system (figure /reffig:pk2).

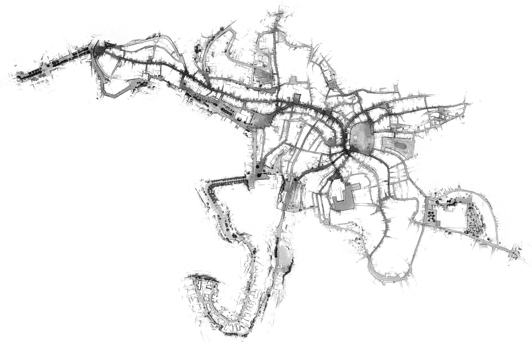

Figure 5: *Siena, Italy: city centre. Total length of trajectories more than 100km.*

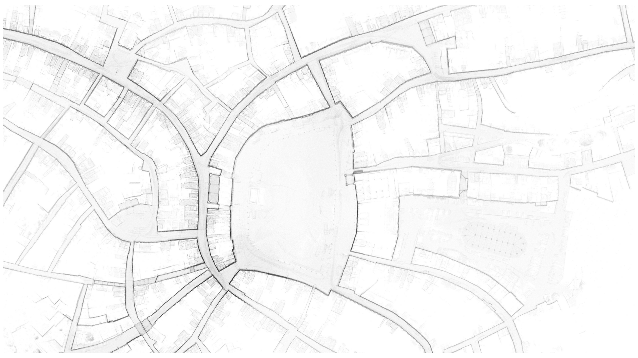

Figure 6: *Siena, Italy: Piazza del Campo - sketch from our system.*

3.7. Facade

It is an outdoor small-scale survey. Figure 17 shows 360 photos from Insta380 X4 that were used for colouring point cloud shown in figure 18.

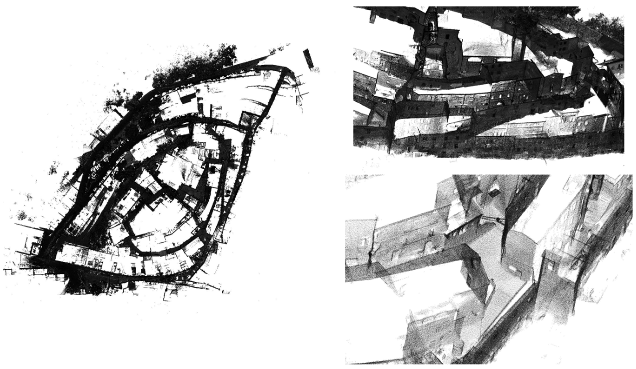

Figure 7: *Chiusdino, Italy.*

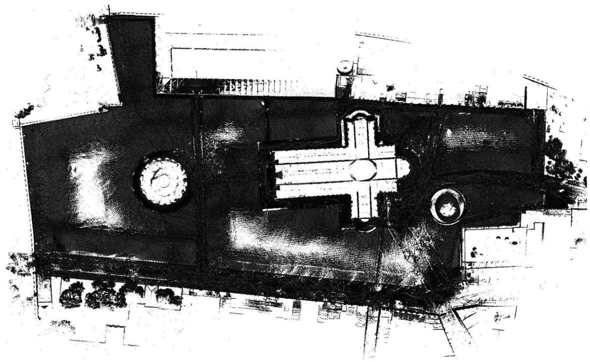

Figure 8: *Pisa, Italy - top view.*

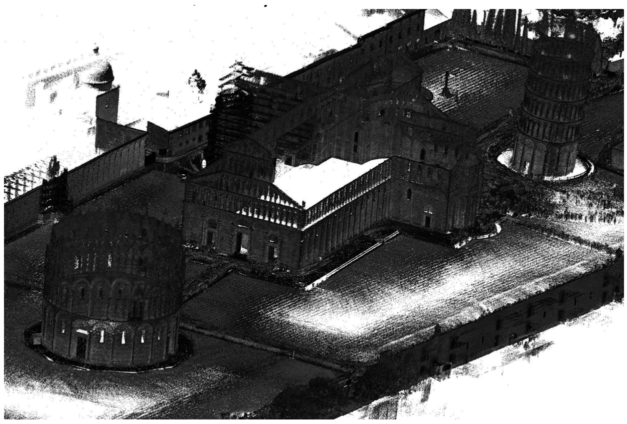

Figure 9: *Pisa, Italy - perspective view.*

4. Accuracy and precision assessment

We encourage Readers to follow https://github.com/MapsHD/HDMapping, especially the section "Knowledge base (accuracy, precision, benchmarks, comparison to other mobile mapping systems etc...)". At this stage of development, we reach precision for LiDAR odometry up to 2cm

Figure 10: *Roccastrada, Italy - top view.*

Figure 11: *Roccastrada, Italy - side view.*

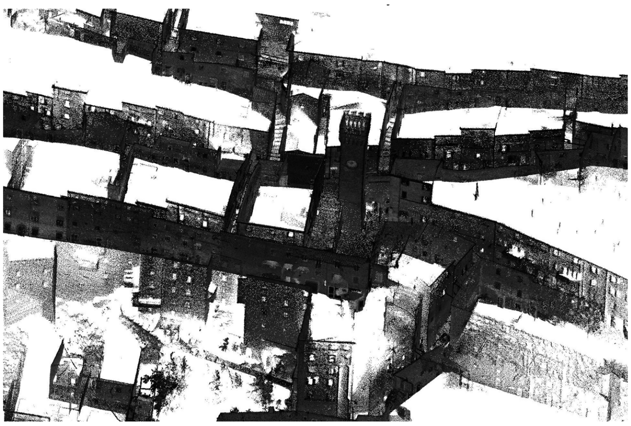

Figure 12: *Roccastrada, Italy - perspective view.*

and accuracy up to 1It means we should expect accuracy up to 1m on a 100m distance. Once we incorporate loop closure and georeferencing we improve this accuracy.

5. Conclusions

This paper describes an open source project https://github.com/MapsHD/HDMapping for large-scale 3D mapping using the open-hardware hand-held LiDAR measurement device available at https://github.com/JanuszBedkowski/mandeye_controller in application of large-scale heritage scenes acquisition and digitization. The project has already more than 100 active end-users providing important feedback for constant development. At the current stage, we provide

Figure 13: *San Gusme, Italy - top view.*

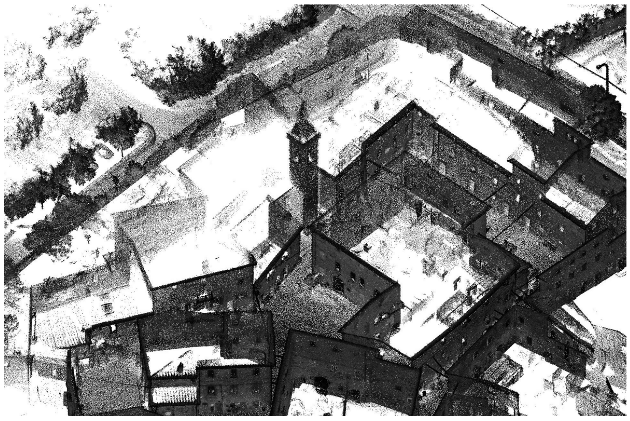

Figure 14: *San Gusme, Italy - perspective view.*

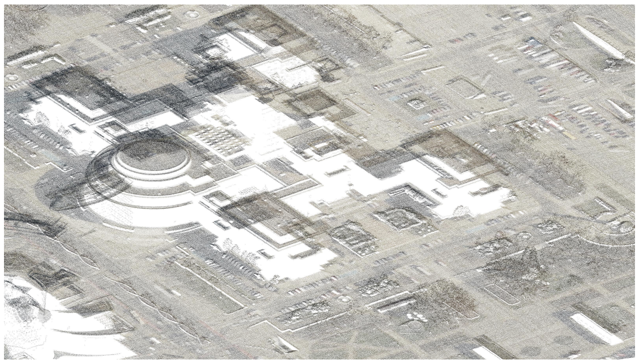

Figure 15: *Palace of Culture and Science, Warsaw, Poland, aerial LiDAR data.*

- multi-view terrestrial laser scanning algorithms (NDT, ICP, etc...),
- LiDAR odometry,
- Pose Graph SLAM (Simultaneous Localisation and Mapping),

Our open hardware mobile mapping system is based on LiVOX MID360 - laser scanner with a non-repetitive scanning pattern equipped with an equirectangular camera. We provided custom synchronization between the camera and LiDAR-based on an LED ring showing timestamps using a Grey code. It enables post-process synchronizing with 100m resolution, thus all image data (8K, 30fps) can be incorporated for further processing. The goal of the project is to provide an affordable mobile mapping system and open-source software that can be widely used also by the Culture Heritage community.

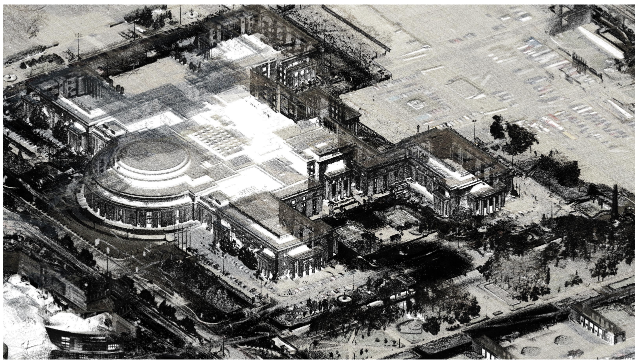

Figure 16: *Palace of Culture and Science, Warsaw, Poland, aerial LiDAR data + handheld mobile mapping data.*

Figure 17: *360 photo from Insta380 X4.*

6. Future work

We are at the beginning of the journey to a fully automated solution that can build 3D coloured maps. Plenty of challenges have to be addressed such as:

- automated multi-session SLAM,
- automated georeferencing,
- automated colouring,
- automated data filtering for noise and outlier removal.

At the current stage of the project, we are happy to claim that it is still an affordable mobile mapping system. It enables making maps for multiple sessions of more than 100km in total.

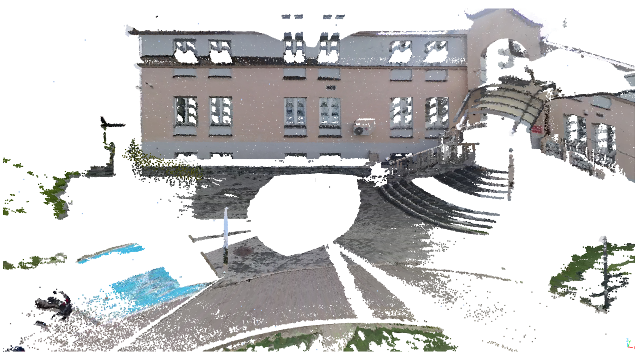

Figure 18: *Colored point cloud of the facade.*

References

[AFDT22] Abaspur Kazerouni I., Fitzgerald L., Dooly G., Toal D.: A survey of state-of-the-art on visual slam. *Expert Systems with Applications 205* (2022), 117734. URL: https://www.sciencedirect.com/science/article/pii/S0957417422010156, doi:https://doi.org/10.1016/j.eswa.2022.117734. 2

[AHLO05] Arias P., Herraez J., Lorenzo H., Ordonez C.: Control of structural problems in cultural heritage monuments using close-range photogrammetry and computer methods. *Computers and Structures 83*, 21 (2005), 1754–1766. URL: https://www.sciencedirect.com/science/article/pii/S0045794905001094, doi:https://doi.org/10.1016/j.compstruc.2005.02.018. 3

[ALGLB*23] Aricò M., La Guardia M., Lo Brutto M., Rappa E. M., Vinci C.: Mobile mapping for cultural heritage: The survey of the complex of st. john of the hermits in palermo (italy). *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences XLVIII-1/W1-2023* (2023), 25–32. URL: https://isprs-archives.copernicus.org/articles/XLVIII-1-W1-2023/25/2023/, doi:10.5194/isprs-archives-XLVIII-1-W1-2023-25-2023. 2

[Bed22] Bedkowski J.: *Large-Scale Simultaneous Localization and Mapping*. Cognitive Intelligence and Robotics. Springer, 2022. URL: https://doi.org/10.1007/978-981-19-1972-5, doi:10.1007/978-981-19-1972-5. 2

[Bed24] Bedkowski J.: Open source, open hardware hand-held mobile mapping system for large scale surveys. *SoftwareX 25* (2024), 101618. URL: https://www.sciencedirect.com/science/article/pii/S235271102300314X, doi:https://doi.org/10.1016/j.softx.2023.101618. 2

[BF24] Bedkowski J., Fitri T. Y.: Novel (re-configurable, wearable, light weight, ergonomic) low cost 3d mobile mapping system not only for extreme mapping applications. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences XLVIII-2/W8-2024* (2024), 25–30. URL: https://isprs-archives.copernicus.org/articles/XLVIII-2-W8-2024/25/2024/, doi:10.5194/isprs-archives-XLVIII-2-W8-2024-25-2024. 2

[BHH*15] Borrmann D., Hess R., Houshiar H. R., Eck D., Schilling K., Nüchter A.: Robotic mapping of cultural heritage sites. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences XL-5/W4* (2015), 9–16. URL: https://isprs-archives.copernicus.org/articles/XL-5-W4/9/2015/, doi:10.5194/isprsarchives-XL-5-W4-9-2015. 2

[BNK*21] Bedkowski J., Nowak H., Kubiak B., Studzinski W., Janeczek M., Karas S., Kopaczewski A., Makosiej P., Koszuk J., Pec M., Miksa K.: A novel approach to global positioning system accuracy assessment, verified on lidar alignment of one million kilometers at a continent scale, as a foundation for autonomous driving safety analysis. *Sensors 21*, 17 (2021). URL: https://www.mdpi.com/1424-8220/21/17/5691, doi:10.3390/s21175691. 2

[CNX*20] Chen S., Nan L., Xia R., Zhao J., Wonka P.: Plade: A plane-based descriptor for point cloud registration with small overlap. 2530–2540. 2

[CPBT24] Conti A., Pagliaricci G., Bonora V., Tucci G.: A comparison between terrestrial laser scanning and hand-held mobile mapping for the documentation of built heritage. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences XLVIII-2/W4-2024* (2024), 141–147. URL: https://isprs-archives.copernicus.org/

articles/XLVIII-2-W4-2024/141/2024/, doi:10.5194/isprs-archives-XLVIII-2-W4-2024-141-2024. 2

[CSVB24] CHAYSRI P., SPATHARIS C., VLACHOS K., BLEKAS K.: Design and implementation of a low-cost intelligent unmanned surface vehicle. *Sensors 24*, 10 (2024). URL: https://www.mdpi.com/1424-8220/24/10/3254, doi:10.3390/s24103254. 2

[DLY*20] DONG Z., LIANG F., YANG B., XU Y., ZANG Y., LI J., WANG Y., DAI W., FAN H., HYYPPÄ J., STILLA U.: Registration of large-scale terrestrial laser scanner point clouds: A review and benchmark. *ISPRS Journal of Photogrammetry and Remote Sensing 163* (2020), 327–342. URL: https://www.sciencedirect.com/science/article/pii/S0924271620300836, doi:https://doi.org/10.1016/j.isprsjprs.2020.03.013. 2

[DPDLG*20] DE PAOLIS L. T., DE LUCA V., GATTO C., D'ERRICO G., PALADINI G. I.: Photogrammetric 3d reconstruction of small objects for a real-time fruition. In *Augmented Reality, Virtual Reality, and Computer Graphics* (Cham, 2020), De Paolis L. T., Bourdot P., (Eds.), Springer International Publishing, pp. 375–394. 3

[EAQ22] ELHASHASH M., ALBANWAN H., QIN R.: A review of mobile mapping systems: From sensors to applications. *Sensors 22*, 11 (2022). URL: https://www.mdpi.com/1424-8220/22/11/4262, doi:10.3390/s22114262. 2

[GFHS25] GHOLAMI FARKOUSHI M., HONG S., SOHN H.-G.: Generating seamless three-dimensional maps by integrating low-cost unmanned aerial vehicle imagery and mobile mapping system data. *Sensors 25*, 3 (2025). URL: https://www.mdpi.com/1424-8220/25/3/822, doi:10.3390/s25030822. 3

[GRE*09] GUIDI G., RUSSO M., ERCOLI S., REMONDINO F., RIZZI A., MENNA F.: A multi-resolution methodology for the 3d modeling of large and complex archeological areas. *International Journal of Architectural Computing 7*, 1 (2009), 39–55. URL: https://doi.org/10.1260/147807709788549439, arXiv:https://doi.org/10.1260/147807709788549439, doi:10.1260/147807709788549439. 3

[HKT22] HOLMBERG M., KARLSSON O., TULLDAHL M.: Lidar positioning for indoor precision navigation. In *2022 IEEE/CVF Conference on Computer Vision and Pattern Recognition Workshops (CVPRW)* (2022), pp. 358–367. doi:10.1109/CVPRW56347.2022.00051. 3

[KAS*13] KARASZEWSKI M., ADAMCZYK M., SITNIK R., MICHOŃSKI J., ZAŁUSKI W., BUNSCH E., BOLEWICKI P.: Automated full-3D digitization system for documentation of paintings. In *Optics for Arts, Architecture, and Archaeology IV* (2013), Pezzati L., Targowski P., (Eds.), vol. 8790, International Society for Optics and Photonics, SPIE, p. 87900X. URL: https://doi.org/10.1117/12.2020447, doi:10.1117/12.2020447. 3

[KNCK22] KARAM S., NEX F., CHIDURA B. T., KERLE N.: Microdrone-based indoor mapping with graph slam. *Drones 6*, 11 (2022). URL: https://www.mdpi.com/2504-446X/6/11/352, doi:10.3390/drones6110352. 2

[KNP*25] KHORAMSHAHI E., NEZAMI S., PELLIKKA P., HONKAVAARA E., CHEN Y., HABIB A.: A taxonomy of sensors, calibration and computational methods, and applications of mobile mapping systems: A comprehensive review. *Remote Sensing 17*, 9 (2025). URL: https://www.mdpi.com/2072-4292/17/9/1502, doi:10.3390/rs17091502. 1

[KVP*19] KARAM S., VOSSELMAN G., PETER M., HOSSEINYALAMDARY S., LEHTOLA V.: Design, calibration, and evaluation of a backpack indoor mobile mapping system. *Remote Sensing 11*, 8 (2019). URL: https://www.mdpi.com/2072-4292/11/8/905, doi:10.3390/rs11080905. 2

[LAH*25] LI Y., AN J., HE N., LI Y., HAN Z., CHEN Z., QU Y.: A review of simultaneous localization and mapping algorithms based on lidar. *World Electric Vehicle Journal 16*, 2 (2025). URL: https://www.mdpi.com/2032-6653/16/2/56, doi:10.3390/wevj16020056. 2

[LBH*15] LAUTERBACH H. A., BORRMANN D., HESS R., ECK D., SCHILLING K., NÜCHTER A.: Evaluation of a backpack-mounted 3d mobile scanning system. *Remote. Sens. 7*, 10 (2015), 13753–13781. URL: https://doi.org/10.3390/rs71013753, doi:10.3390/RS71013753. 2

[LDW91] LEONARD J., DURRANT-WHYTE H.: Simultaneous map building and localization for an autonomous mobile robot. In *Proceedings IROS '91:IEEE/RSJ International Workshop on Intelligent Robots and Systems '91* (1991), pp. 1442–1447 vol.3. doi:10.1109/IROS.1991.174711. 2

[LRS*23] LIANG L., RAO H., SHEN G., WANG C., WU X.: A real-time framework for uav indoor self-positioning and 3d mapping base on 2d lidar, stereo camera and imu. In *2023 IEEE International Conference on Real-time Computing and Robotics (RCAR)* (2023), pp. 280–285. doi:10.1109/RCAR58764.2023.10249971. 3

[Luh10] LUHMANN T.: Close range photogrammetry for industrial applications. *ISPRS Journal of Photogrammetry and Remote Sensing 65*, 6 (2010), 558–569. ISPRS Centenary Celebration Issue. URL: https://www.sciencedirect.com/science/article/pii/S0924271610000584, doi:https://doi.org/10.1016/j.isprsjprs.2010.06.003. 3

[LWG*19] LUO L., WANG X., GUO H., LASAPONARA R., ZONG X., MASINI N., WANG G., SHI P., KHATTELI H., CHEN F., TARIQ S., SHAO J., BACHAGHA N., YANG R., YAO Y.: Airborne and spaceborne remote sensing for archaeological and cultural heritage applications: A review of the century (1907–2017). *Remote Sensing of Environment 232* (2019), 111280. URL: https://www.sciencedirect.com/science/article/pii/S0034425719302998, doi:https://doi.org/10.1016/j.rse.2019.111280. 2

[MKG24] MITKA B., KLAPA P., GAWRONEK P.: Laboratory tests of metrological characteristics of a non-repetitive low-cost mobile handheld laser scanner. *Sensors 24*, 18 (2024). URL: https://www.mdpi.com/1424-8220/24/18/6010, doi:10.3390/s24186010. 3

[MKMea23] MARKIEWICZ J., KOT P., MARKIEWICZ L., ET AL.: The evaluation of hand-crafted and learned-based features in terrestrial laser scanning-structure-from-motion (tls-sfm) indoor point cloud registration: the case study of cultural heritage objects and public interiors. *Herit Sci 11* (2023), 254. doi:https://doi.org/10.1186/s40494-023-01099-9. 3

[MMS*21] MOKROŠ M., MIKITA T., SINGH A., TOMAŠTÍK J., CHUDÁ J., WĘŻYK P., KUŽELKA K., SUROVÝ P., KLIMÁNEK M., ZIĘBA-KULAWIK K., BOBROWSKI R., LIANG X.: Novel low-cost mobile mapping systems for forest inventories as terrestrial laser scanning alternatives. *International Journal of Applied Earth Observation and Geoinformation 104* (2021), 102512. URL: https://www.sciencedirect.com/science/article/pii/S0303243421002191, doi:https://doi.org/10.1016/j.jag.2021.102512. 2

[MRD*21] MONNA F., ROLLAND T., DENAIRE A., NAVARRO N., GRANJON L., BARBÉ R., CHATEAU-SMITH C.: Deep learning to detect built cultural heritage from satellite imagery. - spatial distribution and size of vernacular houses in sumba, indonesia -. *Journal of Cultural Heritage 52* (2021), 171–183. URL: https://www.sciencedirect.com/science/article/pii/S1296207421001606, doi:https://doi.org/10.1016/j.culher.2021.10.004. 2

[MRR05] MANZONI G., RIZZO R. G., ROBIGLIO C.: Mobile mapping systems in cultural heritages survey, cipa 2005 xx international symposium, 26 september - 01 october, 2005, torino, italy. 1

[MT24] M.F.A. L., T. D. K.: Large-scale mapping of the historical underground limestone quarries using mobile laser scanning, a case study in riemst, belgium. *Geoheritage 16* (2024). doi:https://doi.org/10.1007/s12371-024-00981-7. 2

[MTT*17] METCALFE B., THOMAS B., TRELOAR A., RYMANSAIB Z., HUNTER A., WILSON P.: A compact, low-cost unmanned surface vehicle for shallow inshore applications. In *2017 Intelligent Sys-*

tems Conference (IntelliSys) (2017), pp. 961–968. doi:10.1109/IntelliSys.2017.8324246. 2

[MVI*22] MASET E., VALENTE R., IAMONI M., HAIDER M., FUSIELLO A.: Integration of photogrammetry and portable mobile mapping technology for 3d modeling of cultural heritage sites: The case study of the bziza temple. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences XLIII-B2-2022* (2022), 831–837. URL: https://isprs-archives.copernicus.org/articles/XLIII-B2-2022/831/2022/, doi:10.5194/isprs-archives-XLIII-B2-2022-831-2022. 3

[NR14] NEX F., REMONDINO F.: Uav for 3d mapping applications: a review. *Appl Geomat 6* (2014), 1–15. doi:https://doi.org/10.1007/s12518-013-0120-x. 2

[OBAV21] ONIGA V. E., BREABAN A. I., ALEXE E. I., VASII C.: Indoor mapping of a complex cultural heritage scene using tls and hmls laser scanning. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, ISPRS Congress (2021 edition) XLIII-B2-2021 XXIV* (2021), 605–612. URL: https://isprs-archives.copernicus.org/articles/XLIII-B2-2021/605/2021/isprs-archives-XLIII-B2-2021-605-2021.pdf. 2

[OCSR19] ORTIZ-CODER P., SÁNCHEZ-RÍOS A.: A self-assembly portable mobile mapping system for archeological reconstruction based on vslam-photogrammetric algorithm. *Sensors 19*, 18 (2019). URL: https://www.mdpi.com/1424-8220/19/18/3952, doi:10.3390/s19183952. 3

[OLGA20] OTERO R., LAGÜELA S., GARRIDO I., ARIAS P.: Mobile indoor mapping technologies: A review. *Automation in Construction 120* (2020), 103399. URL: https://www.sciencedirect.com/science/article/pii/S0926580520309791, doi:https://doi.org/10.1016/j.autcon.2020.103399. 2

[PGJMSA13] PUENTE I., GONZÁLEZ-JORGE H., MARTÍNEZ-SÁNCHEZ J., ARIAS P.: Review of mobile mapping and surveying technologies. *Measurement 46*, 7 (2013), 2127–2145. URL: https://www.sciencedirect.com/science/article/pii/S0263224113000730, doi:https://doi.org/10.1016/j.measurement.2013.03.006. 2

[PST00] PEDERSINI F., SARTI A., TUBARO S.: Automatic monitoring and 3d reconstruction applied to cultural heritage. *Journal of Cultural Heritage 1*, 3 (2000), 301–313. URL: https://www.sciencedirect.com/science/article/pii/S1296207400010827, doi:https://doi.org/10.1016/S1296-2074(00)01082-7. 3

[REH06] REMONDINO F., EL-HAKIM S.: Image-based 3d modelling: a review. *The photogrammetric record 21*, 115 (2006), 269–291. 3

[Rem11] REMONDINO F.: Heritage recording and 3d modeling with photogrammetry and 3d scanning. *Remote Sensing 3*, 6 (2011), 1104–1138. URL: https://www.mdpi.com/2072-4292/3/6/1104, doi:10.3390/rs3061104. 3

[SAMC*21] SANCHEZ-APARICIO L. J., MORA R., CONDE B., MATE-GONZALEZ M. A., SANCHEZ-APARICIO M., GONZALEZ-AGUILERA D.: Integration of a wearable mobile mapping solution and advance numerical simulations for the structural analysis of historical constructions: A case of study in san pedro church (palencia, spain). *Remote Sensing 13*, 7 (2021). URL: https://www.mdpi.com/2072-4292/13/7/1252, doi:10.3390/rs13071252. 2

[SNRBB25] SUCHOCKI C., NOWAK R., RUTKOWSKI R., BŁASZCZAK-BĄK W.: Using handheld 3d laser scanner and high-resolution handheld digital microscope for hybrid building condition measurements. *Measurement* (2025), 117751. URL: https://www.sciencedirect.com/science/article/pii/S0263224125011108, doi:https://doi.org/10.1016/j.measurement.2025.117751. 3

[SSAF*19] SHAKHATREH H., SAWALMEH A. H., AL-FUQAHA A., DOU Z., ALMAITA E., KHALIL I., OTHMAN N. S., KHREISHAH A., GUIZANI M.: Unmanned aerial vehicles (uavs): A survey on civil applications and key research challenges. *IEEE Access 7* (2019), 48572–48634. doi:10.1109/ACCESS.2019.2909530. 2

[The20] THEMISTOCLEOUS K.: *The Use of UAVs for Cultural Heritage and Archaeology*. Springer International Publishing, Cham, 2020, pp. 241–269. URL: https://doi.org/10.1007/978-3-030-10979-0_14, doi:10.1007/978-3-030-10979-0_14. 2

[TKWR23] TRYBAŁA P., KASZA D., WAJS J., REMONDINO F.: Comparison of low-cost handheld lidar-based slam systems for mapping underground tunnels. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences XLVIII-1/W1-2023* (2023), 517–524. URL: https://isprs-archives.copernicus.org/articles/XLVIII-1-W1-2023/517/2023/, doi:10.5194/isprs-archives-XLVIII-1-W1-2023-517-2023. 2

[TS] TEMILOLORUN A., SINGH Y.: Development of a low cost unmanned surface vessel for autonomous navigation in shallow water. *Conference Proceedings of iSCSS*, GENERAL. URL: http://library.imarest.org/record/11137, doi:https://doi.org/10.24868/11137. 2

[TS24] TEMILOLORUN A., SINGH Y.: Towards design and development of a low-cost unmanned surface vehicle for aquaculture water quality monitoring in shallow water environments, 2024. URL: https://arxiv.org/abs/2410.09513, arXiv:2410.09513. 2

[TSFS0] TAVARIS D., SCANDINO L., FORESTI G. L., SCAGNETTO I.: A cost-effective autonomous underwater system for small size object detection. *Integrated Computer-Aided Engineering 0*, 0 (0), 10692509251336668. URL: https://doi.org/10.1177/10692509251336668, arXiv:https://doi.org/10.1177/10692509251336668, doi:10.1177/10692509251336668. 2

[TWS14] THEILER P. W., WEGNER J. D., SCHINDLER K.: Keypoint-based 4-points congruent sets – automated marker-less registration of laser scans. *ISPRS Journal of Photogrammetry and Remote Sensing 96* (2014), 149–163. URL: https://www.sciencedirect.com/science/article/pii/S0924271614001701, doi:https://doi.org/10.1016/j.isprsjprs.2014.06.015. 2

[Ulv20] ULVI A.: Importance of unmanned aerial vehicles (uavs) in the documentation of cultural heritage. *Turkish Journal of Engineering 4*, 3 (2020), 104–112. doi:10.31127/tuje.637050. 2

[WHP*23] WANG W., HEI M., PENG F., LI J., CHEN S., HUANG Y., FENG Z.: Development of "air-ground data fusion" based lidar method: Towards sustainable preservation and utilization of multiple-scaled historical blocks and buildings. *Sustainable Cities and Society 91* (2023), 104414. URL: https://www.sciencedirect.com/science/article/pii/S2210670723000252, doi:https://doi.org/10.1016/j.scs.2023.104414. 3

[XWL*20] XIAO Y.-L., WEN Y., LI S., ZHANG Q., ZHONG J.: Large-scale structured light 3d shape measurement with reverse photography. *Optics and Lasers in Engineering 130* (2020), 106086. URL: https://www.sciencedirect.com/science/article/pii/S0143816619313879, doi:https://doi.org/10.1016/j.optlaseng.2020.106086. 3

[Yas07] YASTIKLI N.: Documentation of cultural heritage using digital photogrammetry and laser scanning. *Journal of Cultural Heritage 8*, 4 (2007), 423–427. URL: https://www.sciencedirect.com/science/article/pii/S1296207407001082, doi:https://doi.org/10.1016/j.culher.2007.06.003. 3

[YJW*24] YANG M., JIANG K., WIJAYA B., WEN T., MIAO J., HUANG J., ZHONG C., ZHANG W., CHEN H., YANG D.: Review and challenge: High definition map technology for intelligent connected vehicle. *Fundamental Research* (2024). URL: https://www.sciencedirect.

com/science/article/pii/S2667325824000268, doi:https://doi.org/10.1016/j.fmre.2024.01.006. 2

[YYGD07] YILMAZ H., YAKAR M., GULEC S., DULGERLER O.: Importance of digital close-range photogrammetry in documentation of cultural heritage. *Journal of Cultural Heritage 8*, 4 (2007), 428–433. URL: https://www.sciencedirect.com/science/article/pii/S1296207407001094, doi:https://doi.org/10.1016/j.culher.2007.07.004. 3

[ZB14] ZLOT R., BOSSE M.: *Efficient Large-Scale 3D Mobile Mapping and Surface Reconstruction of an Underground Mine*. Springer Berlin Heidelberg, Berlin, Heidelberg, 2014, pp. 479–493. URL: https://doi.org/10.1007/978-3-642-40686-7_32, doi:10.1007/978-3-642-40686-7_32. 2

[ZBG*14] ZLOT R., BOSSE M., GREENOP K., JARZAB Z., JUCKES E., ROBERTS J.: Efficiently capturing large, complex cultural heritage sites with a handheld mobile 3d laser mapping system. *Journal of Cultural Heritage 15*, 6 (2014), 670–678. URL: https://www.sciencedirect.com/science/article/pii/S1296207413002185, doi:https://doi.org/10.1016/j.culher.2013.11.009. 1

[ZBJ*12] ZLOT R., BOSSE M., JUCKES E., GREENOP K., ROBERTS J.: Efficiently scanning remote cultural heritage sites using a handheld 3d mobile mapping system, paper presented at robotics in cultural heritage (rich) 2012. 1