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Unsafe Building: Documenting Heritage at Risk through Robotic and Semi-Autonomous Survey

Keith Challis, National Trust, Heelis, Kemble Drive, Swindon SN2 2NA
Keith.Challis@nationaltrust.org.uk

Lynsey McLaughlin, National Trust, Oxburgh Hall, Oxborough, King's Lynn PE33 9PS
lynsey.mclaughlin@nationaltrust.org.uk

Glen Pearce, National Trust, Orford Quay, Orford, Woodbridge IP12 2NU
glen.pearce@nationaltrust.org.uk

Angus Wainwright, National Trust, Westley Bottom, Bury St Edmonds IP33 3WD
angus.wainwright@nationaltrust.org.uk

Colin Evison, BAM Nuttall, St James House, Knoll Road, Camberley, GU15 3XW
colin.evison@bam.com

Callum Whitfield, BAM Site Solutions Ltd, 2-26 Rixon Road, Finedon Road Industrial Estate, Wellingborough, Northamptonshire NN8 4BB
cwhitfield@bam.com

Jon Bedford, Historic England, 37 Tanner Row, York YO1 6WP
jon.bedford@historicengland.org.uk

Gary Young, Historic England, 37 Tanner Row, York YO1 6WP
gary.young@historicengland.org.uk

Vijay Pawar, University College London, Bartlett School of Sustainable Construction,
1-19 Torrington Place, London WC1E 7HB,
v.pawar@ucl.ac.uk

David Fletcher
cgfletch@gmail.com

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Abstract

The National Trust cares for many places where access to heritage is restricted, for safety or other reasons, limiting the opportunity for monitoring, recording and visitor engagement. The remains of the Atomic Weapons Research Establishment (AWRE) testing facility, built between 1954 and 1962 at Orford Ness on the Suffolk coast of England, represent such a case. The AWRE structures are a Scheduled Monument and sit within a wider landscape of 20thcentury defence heritage. The buildings have attained a mythical status in popular culture and attract substantial visitor interest. However, they are unsafe to enter, and their long-term conservation strategy is to allow their gradual decline to a point where significant evidence is lost, with their ultimate loss to coastal erosion anticipated.

Recognising these challenges our work has sought to develop and assess a prototype use of robotic and semi-autonomous survey technology for heritage at risk in challenging environments. Work used a suite of complementary technologies, including Boston Dynamics quadruped robots, caged and conventional drones combining laser scanning and digital photogrammetry. This paper provides an account of practicalities, benefits, and limitations of robotic and semi-autonomous survey for documenting heritage assets.

Keywords
Heritage at Risk, Defence Heritage, Cold War, Robotics, Laser Scanning, Photogrammetry

Introduction

Landscape and Historical Context

Orford Ness is a 16km long vegetated shingle spit that is connected to the mainland at Slaughden and runs south-east to Hollesley along the Suffolk, (North Sea) coast of eastern England (Figure.1). It is separated from the mainland by the rivers Alde and Ore and between the shingle bar and the mainland is Havergate Island. The Ness's maximum height above sea level is 4m and at its broadest point it is approximately 1.5km wide. The wider part is split south-west to north-east by Stony Ditch, a tidal creek that broadly separates the shingle on the seaward side from the marsh on the river side of the Ness.

In 1913, negotiations for the purchase of the Ness from the Sudbourne Estate for the army's new flying corps began. From 1915, Orford Ness became a site of military testing for the Royal Flying Corps (RFC). The experiments were wide ranging from ballistics experiments relating to bombs and ammunition and aerial tactics to parachutes, night flying equipment and aerial photography. Orford Ness also had a prisoner of war (POW) camp and another camp for either Chinese 'distressed seamen' or Chinese Labour Corps who worked on the creation of the airfield (Heazell, 2011).

Briefly closed in 1920, Orford Ness reopened as a satellite for RAF Martlesham Heath in 1924. Orford Ness was also selected for tests on wireless navigation beacons. Later a different team proved the effectiveness of using radio waves to detect aircraft, a technique later to be known as Radar. Despite its potentially vulnerable location, Orford Ness was used for ballistics testing throughout World War Two (WWII).

Research continued after WWII with testing including ground-strike rockets and heat-seeking missiles. After a devastating flood in 1953, which caused the loss of records and equipment, Orford Ness became the home of the Atomic Weapons Research Establishment (AWRE). New purpose-built laboratories for testing the early atomic weapons were created on the beach whilst the first and second world war buildings that had survived the flood of 1953 were repurposed. New weapons to test required the construction of three new laboratories in the early 1960s followed by the Magazine. Despite attempts to make more use of the laboratories through conducting commercial as well as military tests, the AWRE facility closed in 1971.

After departure of the AWRE the site was used by RAF bomb disposal until 1986. The site then suffered partial demolition and general vandalism. The National Trust acquired Orford Ness in 1993 and opened it to the public two years later.

A major element of the AWRE complex are the vibration testing laboratories and ancillary buildings, erected in 1960 (Figure 2; Cockroft and Alexander, 2009) and which serve as the focus for this study. Originally conceived for testing Blue Streak intermediate range ballistic missiles, the complex was never used for this purpose but instead carried out environmental conditions testing on the WE177A free fall tactical atomic weapon and early Polaris submarine launched ballistic missiles. Nuclear material was not tested at the site, but rather attention focused on the integrity of weapon casings and the impact on the conventional explosive element of nuclear munitions of the extreme environments of launch, flight and delivery. The principal feature of the complex, and its most visible and iconic element, are the two vibration testing laboratories each a reinforced concrete structure comprising a central chamber covered by a flat concrete roof supported my multiple pillars, a design that gives it the appearance of a pagoda. The laboratories were intended to withstand an accidental detonation of up to 400lbs of high explosives with the unconventional roof structure designed to fail and collapse in the event of an explosion, thus containing the effects of blast within the building.

Each laboratory is semi subterranean, built of steel reinforced concrete, revetted on two sides and its roof capped with shingle to provide additional substance to the structure (Figure 3). Internally the buildings are complex with multiple levels, passageways and service areas linked by narrow stairways. The central chamber, with wall mounting positions for various equipment and covered by the pagoda roof structure, served as the focus for testing. Additional structures of conventional design and construction are appended to the outside of each laboratory and provided office and administrative space.

In addition to the two laboratories the complex includes a centrifuge building (E1 on Figure 2) adjacent to the western most laboratory (building E2 on Figure 2) and a separate control room some way from the laboratories and other minor structures (E1 on Figure 2). The entire vibration testing complex covers an area of approximately 12.5ha with buildings linked by a network of metalled trackways across the otherwise bare shingle surface.

All buildings are now semi derelict and largely devoid of original internal fixtures and fittings, presenting the aspect of empty, abandoned shells.

Conservation Context

The remains of the AWRE testing facility were designated Scheduled Monuments in 2014. The majority of the AWRE structures are unsafe to enter and their long-term conservation strategy is to allow their gradual, managed decline (Wainwright, 2009). At Orford, this means that the site is carefully managed, with minimal intervention, primarily for reasons of public safety. The approach is supported by research, monitoring and recording. It respects the changing historical and natural significances as well as the aesthetic character of the landscape and buildings in a dynamic process of change.

An outcome of this strategy is that there is an urgent need to record the buildings of the AWRE before their condition deteriorates further. The AWRE buildings, the iconic pagoda buildings in particular, have attained almost mythical status in popular culture, however, they are presently not accessible to visitors due to their dangerous state. Notwithstanding Orford attracts substantial visitor interest and the potential to repurpose metric survey data to facilitate digital visitor content could open Orford's heritage to a wider audience, including those visitors with mobility restrictions.

Study of the defence heritage of Orford Ness has demonstrated its place at the nexus of important and innovative developments in military technology throughout much of the 20th century with considerable challenges relating to preservation, interpretation, and contemporary resonance (Heazell, 2011; Wainwright 2009; Walters, and Luscombe, 2019). The physical remains of the AWRE itself have been studied and documented in depth by English Heritage, but not surveyed, (Cocroft and Alexander 2009). The unique character of Orford Ness has prompted a range of sensual, phenomenological, and artistic approaches to the landscape and its defence heritage (Davis, 2021; Bartolini and DeSilvey 2020; Macfarlane and Donwood, 2019) that serve to challenge our understanding of place and meaning.

Work using robotic and autonomous survey technology for heritage applications is relatively scarce. The use of autonomous survey in hazardous industrial environments is more common and an overview was provided by Wong et al (2017) and more recently by Schillo (2022).

Past work in the domain of cultural heritage has tended to focus on the utility of drones, either operator controlled or autonomous, for archaeological and architectural survey (Krátký et al 2021; Orengo et al, 2021; Petracek et al, 2023).

Use of robotic surveying equipment in the study of cultural heritage is little documented. Calisi et al (2007) examined the use of robotics and virtual reality for collecting and presenting survey data for cultural sites. Their approach used bespoke tracked robots mounting a variety of sensor, including lidar and digital cameras, and their own viewing software.

The highly innovative work of Giakoumidis and Anagnostopoulos (2024) has documented an analogous use of both spot robots and drones for entirely autonomous survey, with the survey process driven by real time iterative analysis of the collected data and with a focus on increasing the capacity to undertake and reliability of survey of heritage assets.

Aims and Objectives

The present work seeks to extend the application of robotic and semi-autonomous survey in archaeology. Here we define such an approach as the use of robotic platforms (both terrestrial and airborne) mounting various survey sensors, with the platforms primarily under some form of user control, but with a significant element of autonomous action, via automatic stabilisation, fall recovery and the use of detect and avoid mechanisms for hazards and obstacles.

As a secondary objective our work seeks to advance the mechanisms for leveraging archaeological surveys in digital environments, further explore the audience reaction to digital heritage content and begin the long journey of producing an essential and durable digital record of Orford's nationally significant defence heritage.

We have addressed three principal themes around the recording, documentation, and presentation of heritage at risk in challenging environments.

1). Assessing Robotic and Semi-autonomous Survey Technology: the utility of a variety of survey platforms and survey techniques, focusing on the use of semi-autonomous robotic platforms for surveys in buildings which are otherwise unsafe to enter. Work focused on exploring and documenting survey practicalities and developing a field methodology, assessing the quality, precision and accuracy and identifying the survey products and deliverables achievable using this approach.

2). Developing Immersive Digital Visitor Content: the process of translating metric survey data into visitor content. We examined issues of data collation and translation from survey systems to visualisation software and investigated a variety of means of three-dimensional modelling and presentation of survey data with a focus will be on rapid, scalable workflows for leveraging survey data into visitor content.

3). How do Visitors Respond to On-site Digital Content: testing a variety of digital content with visitors to Orford Ness allowing visitor interaction with and exploration of digital content of different types and collecting visitor feedback. We will address the questions of what good digital content looks like and the variety of visitor responses elucidated whether positive or negative.

This paper reports on our first objective, with some comment on objective two. Our final objective will be explored through visitor-facing digital content during the 2024/5 visitor season and will be reported upon through further publication.
The AWRE complex is a substantial site, covering over 130ha with a range of buildings of varying size and complexity. Our prototyping work has focused on the eastern most vibration testing laboratory building (building E3 on Figure 2). This represents an ambitious, but achievable, survey challenge. The building contains multiple levels and facets, offering a suitable technical test for our approach, and since it is unsafe to enter, it has the key attribute of being impossible to survey fully without the use of autonomous platforms.

Although Scheduled Monument, building E3 is in poor condition. Inspection in 2021 noted the corrosion of concrete reinforcements, particularly to the roof pillars and the loss of Perspex glazing from high-level window openings. The two pagoda buildings are highly significant for their role in the history of British nuclear weapons testing and provide a dramatic contribution to the aesthetic value of the Ness.

Material and Methods

Survey Equipment

Field survey of the vibration testing laboratory was undertaken using a suite of complementary survey platforms and sensors divided broadly into ground based and airborne survey.

Ground based survey utilised a pair of Boston Dynamics spot agile mobile robots, each mounting a different terrestrial laser scanner (Figure 4). Spot is a semi-autonomous quadruped robot controlled either via a mobile data link to an operator using a mobile device with management software installed or semi autonomously. Spot can carry a variety of payloads, up to 14kg, negotiate uneven and unstable terrain, including self-righting upon fall, climb slopes of up to +/- 30 degrees and steps of up to 300mm vertical rise. Typical operational duration is 90 minutes between battery charges.

For our survey, spot 1 carried a Trimble X7 terrestrial laser scanner, and a GoPro camera to provide streamed live video and capture video and still imagery. The Trimble X7 supports a scan range of between 0.6 and 80m with accuracy of < 0.3 mm @ 20 m. In addition to the scanning laser the X7 deploys three 10MP coaxial mounted digital cameras, capturing RGB values for each scanned point.

Spot 2 carried a Leica RTC360 terrestrial laser scanner. The RTC360 supports a scan range of between 0.5 and 130m, with an accuracy of 1.9 mm @ 10 m. It also deploys a three camera 360 degree imaging system, collecting hemispherical imagery for standalone viewing and to provide RGB values for scanned points.

Airborne survey was undertaken using an Flyability Elios 3 inspection drone with Ouster OS0-128 Rev 7 LiDAR sensor, for internal spaces (Figure 5), and a DJI Matrice 300 drone with 45MP P1 camera for external survey.

The Elios 3 is a caged quadcopter, specifically designed for operation in challenging internal spaces. The drone is operator controlled but with an active detect and avoid system designed to minimise risk of impact with objects. It offers a flight time of up to 9 minutes and mounts an Ouster OS0-128 Rev 7 LiDAR sensor, operating on the SLAM principle with a range of up to 100m and a maximum accuracy of +/- 6mm.

The DJI Matrice 300 is an operator-controlled or autonomous quadcopter with a typical flight duration of 45 minutes and deploying a gimbal mounted P1 full frame digital camera with 35mm lens able to capture 45MP still images in RAW or TIFF formats.

Survey Methodology

The External elevations of the vibration testing laboratory were surveyed using a combination of spot deployed laser scanning and drone photography. In practice, spot acted as, in effect, a mobile tripod for the laser scanner guided by the operator to appropriate scan locations at which the deployed scanner is remotely operated, before moving to the next location. In this way a complete scan of the external elevations was accomplished from 29 individual survey stations. A significant feature of the external aspect of the laboratory is the substantial shingle embankments which revet two of the external wall and enhance blast protection. The angle of slope of the shingle embankments is typically more than 40 degrees, which is close to or beyond the recommended operational parameters for spot. In practice, spot was able to negotiate the loose shingle slopes with some difficulty. In most instances spot was positioned by the operator at reasonably stable external locations on the shingle slopes from which it could operate with minimal risk of fall damage.

Less accessible external aspects of the laboratory, and the shingle capped roof structure, were photographed using the Matrice 300 drone.

Internally, the laboratory presented significant surveying challenges. The building has several levels and includes steep, narrow stairways, unprotected drops of several metres and areas with significant blocking debris.

Spot was used in areas accessible from ground level. However, the internal stairways were beyond its operational parameters and presented too great a risk of damage and loss to allow its use. Most of the internal survey was undertaken using the Elios 3 drone and its lidar scanner. Its small size and manoeuvrability allowed the drone to penetrate deeply into the complex building. However, the substantial reinforced concrete structure degraded wireless reception, affecting the operator's ability to control the drone. This, coupled with some areas of substantial blocking debris and the tendency for the downdraft from the drone's rotors to disturb loose material, producing a debris cloud impairing visibility and operational capability, meant that some areas of the internal structure could not be surveyed.

Simultaneously with the detailed survey of the vibration testing laboratory, a wider ranging, context setting survey of the whole vibration testing complex was undertaken using the Matrice 300 drone. This survey concentrated on the collection of imagery suitable for medium resolution photogrammetric modelling of the external elevations and roof structures of the wider complex.

In total, survey was undertaken over a period of 1.5 working days, with survey teams working in parallel on distinct aspects of the key structures and wider complex. Survey was complicated both by the challenges presented by the laboratory and the fact that the site is accessible by boat only, located c.3.5km from the landing stage, and 3km from the nearest electricity supply for charging the many batteries required by the various equipment. Access was also limited by the need to avoid areas of shingle beyond the metalled trackway network traversing the area due to the risk of encountering unexploded ordnance.

Data processing and collation

Survey data from the various systems used was collated and processes using the bespoke software systems provided by each system vendor. Photogrammetric processing was undertaken using Agisoft Metashape Professional. Survey of this sort, comprising data of diverse types, collected by a variety of not necessarily compatible systems, presents its own problems. To overcome compatibility issues, after initial processing, all point cloud data was assembled in the open e57 format. Subsequently, Epic Games Reality Capture was used as the software platform to collate and combine the laser scanned and photogrammetrically derived data to generate a complete, high resolution 3D model of the vibration testing laboratory and its wider context. The model was then utilised in various other software packages to produce standard survey products, mirroring the steps used to generate such deliverables from conventionally deployed survey equipment. The 3D model was used to generate orthorectified image elevations and plans of the laboratory.

Results

Data Collected

Laser scanning equipment on the spot robots collected data from 29 survey stations in and around the vibration testing building, in all recording a total of 413 million points and generating a survey of c.5mm ground sampling distance (GSD) and an overall cloud-to-cloud registration error of 2.178 mm.

The Elios 3 drone mounted lidar collected 284 million points and 1994 images from within the building, generating a survey of 1.25mm GSD and a RMS error of 1.09mm.

The DJI Matrice 300 was used to collect 6509 images of the vibration testing building and its wider context, for photogrammetric processing generating a survey of 5mm GSD and a RMS error of 1.46mm.

In total work generated c 1.5TB data comprising point clouds, photographs and survey metadata.

Survey Deliverables

The final 3D Model (Figure 6) produced by combining cleaned data from the three survey platforms within Reality Capture software has a GSD of 10mm. The model enables viewing of the building in both perspective and orthographic projections. Transverse slices through the model can be taken at any location and on any plane, revealing the internal structure of the building.

Orthoimages of principal elevations were generated using VCL's Meshlab open-source mesh manipulation software (Figure 7 and 8). Directly analogous to line drawn elevations but containing the rich textural and architectural details of a photograph, the orthoimages provide a highly effective means of presenting and interpreting the building in true scale orthographic form and are quicker to generate and contain richer detail than drawings.

Conventional line drawn elevations and plans (Figure 9) were produced by on screen digitising from the orthoimages using Inkscape technical illustration software. The principal use for drawings in this instance is to provide a clear, easy to interpret outline which highlights significant architectural and structural features using line type and weight and by omission of occluding detail and surfaces. Drawings follow a simplified version of the conventions set out in the most recent guidance from Historic England (Historic England 2024).

Discussion

All the equipment used performed well, either meeting or exceeding its documented operational parameters.

Airborne survey of the external aspects of the laboratory and its wider context using the Matrice 300 drone followed the well documented practice of structure from motion photogrammetry for documenting historic buildings (Historic England 2017) and as such need not be further discussed here.

External laser scanning using spot was effective on level areas, even given the uneven terrain and shingle surface, which it negotiated effectively. Spot struggled on the steeply sloping shingle areas, requiring operator intervention to facilitate safe access. It is worth noting that intervention was largely mediated by the desire to prevent potential fall damage to spot and its payload. This reflects the users' perception of priority, ie protecting valuable equipment rather than pressing on to achieve results regardless of risk. In situations where results were imperative it is likely that pushing spot beyond the subjective limits of acceptable risk would produce results.

Scanning results using both the Trimble and Leica equipment were as would be anticipated from conventional tripod mounted equipment and in this sense, spot provided a stable, robotic platform able to traverse challenging terrain and reach denied areas and produce results mirroring conventional survey platforms.

The more challenging internal aspects of the laboratory require further discussion. The principal challenges to effective survey were presented by the complex, multi-level nature of the laboratory, its substantial construction (of reinforced concrete and external shingle revettment) and the presence of debris caused by the gradual deterioration of the structure.

The multi-level structure presented significant, ultimately insurmountable challenges for spot. The robot platform performed well on level surfaces and was able to negotiate uneven surfaces and scattered debris. However, the steep, narrow concrete steps within the laboratory exceeded spot's operational capability. Again, it should be noted that to some extent this reflects operator perception of risk, particularly in relation to the proximity of unprotected drops. The fact that even a minor failure of spot to maintain balance could lead to a catastrophic outcome was sobering and amplified by the fact that since user access to the laboratory was not possible any loss would be permanent and expensive. A potential mitigation of this risk might be the attachment of a lifeline, allowing retrieval without entering a building, although in this instance this was not attempted.

The principal means of internal survey of the laboratory was the Elios 3 drone. This performed well, able to negotiate complex narrow passageways with relative ease, penetrate and record deeply within the complex structure. Ultimately, the main limitation of use of the Elios 3 was the risk of loss of wireless connection between drone and operator resulting from signal attenuation caused by the reinforced concrete structure. This led to operator decisions to stop survey when connection to the drone deteriorated, again largely driven by risk perception based on the potential loss of valuable equipment. The Elios 3 is designed to land safely where it is on loss of signal, so while catastrophic damage to equipment was unlikely, the inability of the operator to enter the structure and retrieve the drone would have rendered any loss permanent. Signal attenuation may potentially be mitigated by the provision of local wireless or 5G radio hotspots to improve signal strength in complex structures, but was not attempted in this instance.

The data collected by the Elios 3 lidar proved of good quality. Surfaces were clearly recorded with good resolution and colour detail from simultaneously collected imagery. The SLAM nature of the sensor inevitably produces results of lower precision and accuracy than those rendered by a tripod mounted scanner. However, assessment of the data collected suggest that it is well within published accuracy (Flyability 2024) and Elios 3 data combined well with that from the spot mounted scanners and photogrammetric data.

The 3D model of the vibration testing laboratory produced through combination of data from all sensors and platforms provides an effective, high-fidelity record of a complex structure. It might be argued that such renderings are in fact the most effective means of documentation and presentation for interpretation of this and similar structures.

Our assessment is that the record of the laboratory is of a similar standard to that achievable via conventionally deployed survey equipment given the complexity of the structure and presence of internal debris. It is worth noting that 2D orthoimage elevations and CAD drawings struggle to effectively convey the complexity of such a multi-level structure, particularly to an audience less familiar with the conventions of architectural drawings.

Further, the presence of substantial, sloping shingle revetments on two of the principal elevations render drawn and orthoimage presentation challenging. The ability to extract from the complexity and varied materiality the true elevation and plan, minus revetment, is a useful facet of the drawn record.

The facility to present the 3D record via online platforms such as SketchFab (nb link to final model needed for publication) elegantly fulfils a principal aim of the survey – that a building otherwise inaccessible to the public might be made available and explorable digitally.

Conclusions

In this paper we have focused largely on the ability of robotic and semi-autonomous technology to deliver conventional survey products, demonstrating that such survey is able to produce results equal to conventional survey practice. Given environments presenting limited access for the human surveyor robotic and semi-autonomous survey is a viable and effective alternative.

The chief limitations of these techniques are presented by structural features (steps, slopes, debris) that exceed the operational limits of the equipment in the case of spot and signal attenuation affecting operator control in the case of Elios 3. It has been noted that in both instances the actual limitations on what may be surveyed are more likely to be imposed by subjective operator perception of risk, rather than the true limits of the equipment used and that potential ameliorating solutions exist.

At Orford Ness, our trial survey of vibration testing laboratory building E3 has been a signal success. Over the next few years National Trust plans to extend survey to the other structures within the wider AWRE complex – of necessity substantially through robotic and autonomous survey. The results from our first seasons of work will form the basis of in-visit digital content which will be tested over the coming (2024/5) season to help understand the extent to which such material can mitigate the lack of access to unsafe structures and to gain insight into the kinds of digital content that are most accessible and enjoyable for our visitors.

Spot proved to be both a TV star (drawing considerable TV and media interest in our work) and a draw for visitors, with visitor numbers to Orford over the 2023 seasons exceeding those of previous years. For National Trust this is a double benefit of the work, which has allowed us both to document a fragile and unsafe building before its inevitable deterioration and serve the interests of our members and visitors by highlighting the unique heritage of the Ness and improving access to its intriguing and evocative buildings.

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Figure Captions

1 Map showing the location of the AWRE at Orford Ness.

2 Plan showing the complete AWRE vibration testing complex, including building E3, the subject of the survey. From Cocroft and Alexander, 2009, fig. 52.

3 The two vibration testing buildings (building E2 in the foreground with E3 behind) with separate centrifuge building F1 (not part of the complex) visible in the background. ©National Trust Images/Justin Minns.

4 The spot agile mobile robots shown deploying the Trimble x7 (right) and Leica RTC360 (left) laser scanners.

5 The Flyability ELIOS 3 drone.

6 Perspective view of the final 3D model of building E3 looking to the northeast.

7 Orthoimage elevations of building E3.

8 Building E3, external south orthoimage elevation (top) and cutaway to reveal detail of internal structure and subterranean levels (bottom).

9 Orthoimage south elevation of building E3, with derived and drawing.