Institution: Nottingham Trent University (NTU)

Unit of Assessment: B12 – Engineering

Title of case study: New optical instruments have transformed conservation and curatorial practices of dating, displaying and conserving priceless and irreplaceable cultural heritage assets

Period when the underpinning research was undertaken: 2005 to 2020

Details of staff conducting the underpinning research from the submitting unit:

Names:	Roles:	Periods employed by submitting HEI:
Haida Liang	Professor	2005-present
C. S. Cheung	Research Fellow	2010-present
Sotiria Kogou	Research Fellow	2017-present

Period when the claimed impact occurred: 1 August 2013 to 31 July 2020

Is this case study continued from a case study submitted in 2014? No

1. Summary of the impact

NTU has developed novel optical instruments and has examined irreplaceable, priceless and fragile cultural assets, revealing crucial details whilst avoiding traditional damaging invasive sampling methods. The NTU team enabled the Louvre's successful 2016 restoration of Leonardo da Vinci's "Saint John the Baptist" and changed conservation practices which impact all museums in France. NTU's analysis enabled public display of rare Daguerreotype photographs of Charles Darwin's family at Down House, Royal Bed Hangings at Audley End House, and enabled public display of "Acanthes" in the "Henri Matisse: The Cut-Outs" exhibition at the Tate Modern, the most successful Tate exhibition which attract 562,622 visitors, and the Museum of Modern Art in New York. NTU's mobile optical imaging and remote sensing methods transformed understanding about the Buddhist wall paintings at the Mogao Caves UNESCO World Heritage Site in Dunhuang, China and changed dating analysis of wall paintings along the Silk Road.

2. Underpinning research

Research by the Imaging and Sensing for Archaeology, Art History and Conservation (ISAAC) group at Nottingham Trent University (NTU) led by Professor Haida Liang has focused on the development of a complementary suite of cutting-edge non-invasive imaging and spectroscopy techniques including Optical Coherence Tomography (OCT), Microfade Spectrometry, and ground based remote spectral imaging (PRISMS), as well as their application to conservation and historical understanding of cultural heritage.

NTU ISAAC group's PRISMS non-invasive remote spectral imaging system for cultural heritage, funded by EPSRC (**G1**), is the first such system that allows simultaneous reflectance spectral imaging at sub-millimetre resolution combined with 3D mapping, at stand-off distances of tens of metres from a fixed position on the ground (**R1**). This system was developed specifically for automatic high-resolution spectral imaging of large paintings, painted surfaces and wall paintings in churches, temples, palaces and monuments to identify materials and record the state of preservation of entire architectural interiors. It has been adopted by the IPERION HS European Research Infrastructure for Heritage Science as part of the pan-European Mobile lab offerings.

Liang was one of the first to show that the medical imaging technique OCT could be applied to the non-invasive analysis of artworks. OCT, an optical technique based on the Michelson interferometer, is normally used for non-invasive 3D volume imaging of the eye. The study, selected as an editors' choice by the journal *Science*, showed how OCT could visualise the sub-surface microstructure of paintings (**R2**). Through cross-disciplinary collaborative funding (£1M), including from the Leverhulme Trust (**G2**) and EPSRC/AHRC (**G3**), the NTU ISAAC group developed a range of cutting edge mobile OCT systems tailored to the special needs of the cultural heritage sector, applying these techniques in museums and publishing over 30 papers.

Traditional commercial biomedical OCT systems had significant resolution and depth of penetration limitations and were restricted to wavelengths of 800nm-1300nm. An NTU-led AHRC/ESPRC funded (**G3**) research collaboration developed the world's first "Long Wavelength OCT" at 1960nm with the best depth of penetration in materials with low water content (**R3**), partnering with the National Gallery, English Heritage, Southampton University, and optical component manufacturer Gooch & Housego PLC. This collaboration also developed real-time "Ultra High-Resolution OCT" that is non-invasive whilst matching or exceeding the resolution and

contrast of conventional invasive paintings analysis techniques. These cutting-edge OCT systems were successfully tested on a 16th century copy of a Raphael painting at the National Gallery (**R4**), and their efficacy were demonstrated for a range of cultural assets including water transport in sandstone (relevant to Neolithic rock art in the care of Historic England), and the British Museum's collection of ancient Egyptian faience, ancient Jade and Limoges enamels.

The ISAAC group at NTU developed a Microfade spectrometry instrument to measure the light sensitivity of museum collections for preventive conservation. A trade-off, of vital importance to museum, gallery and library curators and conservation professionals, is that whilst artworks are sensitive to light-induced damage, they need to be properly illuminated when on public display to provide best visitor experience as part of the museum and gallery's funding and public missions. The Tate co-funded (**G4**) the NTU ISAAC group's development of the first automated portable and flexible Microfade spectrometry that is capable of identifying the light sensitivity of watercolour paintings to the high degree of accuracy required to determine optimum exhibition conditions (**R5**).

Research conducted by NTU's ISAAC group has led to the development of a new versatile, modular and mobile analytical platform that consists of imaging and spectroscopy systems, that operate from stand-off distances of <3m (close range) to tens of metres (long range), for material identification and monitoring of degradation/corrosion (**R6**). NTU ISAAC's research on a holistic approach to the non-invasive analysis of artworks by combining OCT with a complementary set of spectroscopic/imaging techniques including the minimally micro-invasive microfade spectrometry has defined the analysis strategy of the ISAAC Mobile Lab which has been used in situ on a range of historical artefacts in museums and archives from paintings, manuscripts to enamels and historical sites around the world from the UK to China and the USA.

3. References to the research

High underpinning research quality evidenced by rigorously externally peer reviewed outputs:

R1. Liang H., Lucian A., Lange R., Cheung C., Su B., "Remote spectral imaging with simultaneous extraction of 3D topography for historical wall paintings", *ISPRS Journal of Photogrammetry and Remote Sensing* **95**, 13-22 (2014) https://doi.org/10.1016/j.isprsjprs.2014.05.011
R2. Liang H., Gomez Cid M., Cucu R.G., Dobre G.M., Podoleanu A.Gh., Pedro J.,Saunders D., "En-face Optical Coherence Tomography - a novel application of non-invasive imaging to art conservation", *Optics Express* **13**, 6133-6144 (2015). https://doi.org/10.1364/OPEX.13.006133
R3. Cheung C. S., Daniel J., Tokurakawa M., Clarkson W. A., Liang H., "High resolution Fourier domain optical coherence tomography in the 2μm wavelength range using a broadband supercontinuum source", *Optics Express* **23**(3), 1992-2001 (2015) https://doi.org/10.1364/OE.23.001992
R4. Cheung C. S., Spring M., Liang H., "Ultra-high resolution Fourier domain optical coherence tomography for old master paintings", *Optics Express* **23**(8), 10145-10157 (2015) https://doi.org/10.1364/OE.23.010145
R5. Lerwill A., Brookes A., Townsend J., Hackney S., Liang H., "Micro-fading spectrometry: investigating the wavelength specificity of fading", *Applied Physics A* **118**, 457-463 (2015) https://doi.org/10.1007/s00339-014-8645-3
R6. S. Kogou, G. Shahtahmassebi, A. Lucian, H. Liang, B. Shui, W. Zhang, B. Su and S. van Schaik, "From remote sensing and machine learning to the history of the Silk Road: large scale material identification on wall paintings", *Scientific Reports* **10**, Article number 19312 (2020) https://www.nature.com/articles/s41598-020-76457-9

The high quality of the underpinning research is further indicated by the significant investment in the research and its dissemination obtained competitively from a range of prestigious funders:

G1. "Portable remote hyperspectral imaging for in situ examination of wall paintings", Funder: EPSRC, Grant EP/E016227/1, £209k, 2007 to 2009
G2. "Application of a new non-invasive technique OCT to paintings conservation", Funder: Leverhulme Trust, Grant F01374F, £126,480, 2006-2009
G3. "The Next Generation of Optical Coherence Tomography for Art Conservation", Funder: EPSRC/AHRC Science and Heritage Programme, Grant AH/H032665/1, £661k, 2010-2013

G4. "Development of a micro-fading technique as part of the 'Anoxic Display Frames for Works of Art on Paper'". Funder: The Tate Gallery, £10k, 2006 to 2009

4. Details of the impact

4.1 *Impacts on culture and society, and professional practice:* Enabling precision restoration of an internationally important painting, in collaboration with Louvre Museum professionals, leading to adoption of improved conservation practices across France.

- *Successful restoration of Leonardo da Vinci's "Saint John the Baptist", working in close partnership with The Louvre's conservators.*

The NTU ISAAC group's "Ultra-High Resolution OCT" directly guided the Louvre Museum (Paris, France) conservator's varnish cleaning restoration strategy of Leonardo da Vinci's "Saint John the Baptist". The restoration was in preparation for the 2019 exhibition *Leonardo da Vinci at the Louvre* to mark the 500-year anniversary of the death of the artist in France. According to the exhibition programme, "Saint John the Baptist" is considered to be one of da Vinci's masterpieces and is one of the 3 paintings that he was working on at the end of his life (there are only 15 paintings securely attributed to him world-wide). The painting had not been cleaned since 1802 and its surface had darkened because many layers of varnish applied over the centuries had considerably degraded. Cleaning this irreplaceable and fragile painting took place under immense scrutiny, since the previous restoration of da Vinci's "The Virgin and Child with Saint Anne" was criticized for modifying the painting due to "over-cleaning", prompting staff resignations (Jean-Pierre Cuzin, Le Monde, 2012). NTU's ISAAC group undertook OCT imaging of the layers of varnish on "Saint John the Baptist", working alongside The Louvre's restorer and conservation scientists. Informed by the OCT images, nearly half of the original 15 layers of varnish were meticulously removed without damaging the underlying painting. Indicators of the reach and significance of this impact include media professional Danny Lewis's (Smithsonian Magazine) evaluative review, which heralded the cleaning as "*a success*" noting that "*The restored version also pulls da Vinci's murky details in the forefront once again*" (**S1**). French Ministry-level professional body testimony of the impact is provided by the Director of the Centre for Research and Restoration of the Museums of France, French Ministère de la Culture: "*The NTU developed ultra-high resolution OCT was used to assist with the conservation of Leonardo Da Vinci's painting of St John the Baptist in the Louvre Museum in 2016. The new non-invasive imaging technique allowed a useful immediate feedback to conservators while cleaning old varnish from a painting to control the process. This changed our approach to conservation.*" (**S2**).

- *Adoption of NTU-pioneered methods has led to improvements to conservation practices to all museums in France*

The success of The Louvre and NTU ISAAC collaborative restoration work led directly to the Centre for Research and Restoration of the Museums of France (C2RMF) incorporating OCT analysis (since 2018) "*into our conservation practice for routine cleaning of varnished paintings*" (**S2**). The reach of this impact is over 1,200 museums in France, "*Not only has Professor Liang's research had a significant impact on the way we conserve paintings, but as C2RMF is responsible for the research and restoration of cultural heritage in all museums in France, the change in our conservation practices as a result of this collaboration impacts all museums in France*" (**S2**).

***4.2. Impacts on culture and society:* optimising art galleries' and museums' display policies to enable greater visitor access and enhanced public experience, whilst ensuring that exhibition doesn't damage or degrade irreplaceable cultural artefacts.**

- *Enabling the public display of "Acanthes" in the "Henri Matisse: The Cut-Outs" exhibition of the artist's work at the Tate Modern in London and the Museum of Modern Art in New York*

The NTU ISAAC group worked, under commission, with the Beyeler Foundation in Switzerland to evaluate the light sensitivity of Henri Matisse's "Acanthes" (1953, 3.1 x 3.5 m), which is significant as a major work in the artist's series of large-format papiers découpés. Chromatic modifications and fading of coloured art pieces can change their colour impression from what was originally intended by the artist. NTU's micro-fading examinations established "*prognoses about the stability of individual colours when exposed to light. Such prognoses have an impact on the frequency and length of time for which Acanthes can be presented"* (**S3**). The Chief Conservator at the Beyeler

Foundation has confirmed that the NTU Microfade study gave the Foundation the confidence to loan "Acanthes" to the Tate Modern for a key role in its exhibition "Henri Matisse: The Cut-Outs" from April to September 2014 (**S4**), with concurrent broadcast "Matisse Live" to 15,000 cinema goers, and to loan the piece to continue the tour to the Museum of Modern Art, New York (**S5**), where it was displayed from October 2014 to February 2015. The Tate testified to the reach of the impact in their press release, titled "*Matisse is Tate's most successful exhibition ever*", on 15 September 2014 which stated that "*Henri Matisse: The Cut-Outs received 562,622 visitors making it the most popular exhibition ever held at Tate and the first to receive over half a million people*".

- *Enabling English Heritage to publicly display Daguerreotype photographs of Charles Darwin's family at Down House and to publicly display Royal Bed Hangings at Audley End House*

The NTU ISAAC group, working with English Heritage, used NTU's OCT techniques to elucidate the degradation processes of cover glasses of a unique series of Daguerreotype photographs of Charles Darwin's family. This included the only known image of Darwin with another person (according to the Darwin Correspondence Project, Cambridge University Library). A Senior Conservation Scientist at English Heritage, testified to this work's impact: "*Professor Liang's ground breaking ultra-high resolution optical coherence tomography equipment was instrumental in understanding the decay phenomena and making the decision to replace the glass and remediate the showcase environments to allow this unique cultural heritage to continue to be appreciated by the 71,000 visitors* [to Down house] *per annum*." (**S6**).

The NTU ISAAC group undertook Microfade spectrometry surveys of light sensitivity of historically significant "Royal bed hangings" (1786) and carpets which is part of the visitors guided tour of Audley End House, one of the largest country houses of the Jacobean era, and one of the few fully furnished houses in English Heritage's portfolio. The State Bed of embroidered Chinese silk, commissioned by Sir John Griffin for an anticipated visit by George III, is an important surviving example of a late18th century bed and was made by the London firm Chipchase and Lambert in 1786 at a vast cost. NTU's automated microfade spectrometer permitted accurate on-site analysis. The Senior Conservation Scientist at English Heritage testified to the impact of this work: "[Professor Liang's work] *clearly showed light sensitivity, which spurred the project team to display those rooms in an evening setting*. [The successful redevelopment] *project caused a 30% uplift in visits for the 3 years after completion, thus returning the investment within that period*" (i.e. a 30,000 increase in visitor numbers per year), and furthermore, "*The display has inspired several other heritage organisations, including the National Trust and Parks Canada, to consider this novel approach to light management for sensitive artefacts*" (**S6**).

4.3. *Impacts on culture and society:* transformation to curation, understanding and interpretation, of artworks, leading to lasting adoption of improved analysis practices.

- *NTU remote imaging and multi-modal analysis methods transformed understanding about the Buddhist wall paintings in Cave 465 of the Mogao Caves UNESCO World Heritage Site on the Silk Road, in Dunhuang, China.*

The Mogao Cave temple complex near Dunhuang, China is a UNESCO World Heritage Site along the ancient Silk Road at cross-roads of trade, religion, technology and cultural influences. There are 492 cave temples painted ceiling to wall with masterpieces of Buddhist art from 4th to 14th century with a total of 45,000 square meters of murals and are strongly linked to the history of transcontinental relations and of the spread of Buddhism throughout Asia. Cave 465 at the northern end of the site, has wall paintings in a unique Indo-Tibetan tantric Buddhist style with the full range of Mahāyoga tantric Buddhist imagery (**S7**). These paintings are culturally important because there are few extant pre-14th century Tibetan or Indian/Nepalese tantric Buddhist paintings. The time of construction of this cave was unknown before the work of the NTU ISAAC group, with Dunhuang Research Academy, the custodians of the site, stating that "*There are different opinions on the construction time of this cave. Some scholars suggest that it was as early as the late Tang (9th Century). However, from the history of the lineages, it is obvious that it would not have been made before the 11th Century*" (**S8**).

The NTU ISAAC group's expertise allowed accurate recording of not only high-resolution colour images but more importantly the painting materials identified through their characteristic spectra and the 3D surface of the wall paintings, all under safe imaging conditions. This was done through

the *in situ* use of mobile complementary imaging and spectroscopy instruments, including novel optical instruments developed specifically for cultural heritage such as the PRISMS ground based remote spectral imaging system for automated survey of large wall/ceiling paintings, OCT for revealing preparatory sketches and subsurface cracks, and microfade spectrometry to ensure the illumination required for imaging does not cause damage to the paintings (**S8**).

The NTU study dated the Buddhist wall paintings in Mogao Cave 465 to be from the late 12th to 13th century using the evidence collected by the suite of non-invasive instruments. The Deputy Director of Dunhuang Research Academy stated that, "*This conclusion is significant and long awaited by scholars working on Buddhism in Eastern Central Asia, because it settles a long dispute, over 50 years, amongst experts of this unique cave temple and the era over which major Buddhist caves were constructed in Dunhuang. This collaboration with Professor Liang's team provides important new knowledge, tracing the spread of Buddhism from India to Tibet, the Tangut realm and to China*" (S8). Over 30 historians (~190k total followers) tweeted about these results within the first 2 months following publication. Assoc. Prof of Asian Art S. Huang's (Rice University, US) tweet, "*The most updated scientific study of the Dunhuang Mogao Cave 465 offers yet an additional perspective helpful for dating the cave*" was re-tweeted by art historian Prof C. Clunas (Oxford, UK) (**S9**). Curator of Central Asian Art, Museum für Asiatische Kunst (Berlin, Germany), Dr L. Russell-Smith tweeted "*Exciting find revealed by automatic remote reflectance spectral imaging of mural paintings*" (**S9**). This finding was also featured by Indian National Media (**S10**).

Inspired by the study of Mogao Cave 465, Dunhuang Research Academy assisted Professor Liang's group to survey 7 more caves at the site (**S8**). The Deputy Director of Dunhuang Research Academy stated that, "*Professor Liang has provided extremely valuable information from her remote spectral imaging survey that links the material composition of artworks to historical periods. This important work has provided compelling evidence that the wall paintings in two of the caves had been attributed to the wrong period*" (**S8**).

- *Adoption of NTU-pioneered dating analysis practice for all wall paintings sites under the care of Dunhuang Academy*

The Dunhuang Research Academy (Dunhuang County, Gansu Province, China), is a Chinese national comprehensive institution that has been given responsibility by the Chinese Government for the conservation, management and research of the Mogao Caves (a world cultural heritage site at Dunhuang), as well as for the Yulin Caves (a nationally protected key cultural heritage site at Guazhou), and the Western Thousand-Buddha Caves at Dunhuang (S7). The Deputy Director of Dunhuang Research Academy confirmed that the "*Academy's adoption of Prof Liang's specific techniques has changed the practice of Dunhuang Research Academy's researchers who study the Mogao Caves. In collaboration, we are now adopting this method more broadly for dating of other caves such as those currently dated to the Tangut period (total of over 80 such caves) and have also purchased an OCT for routine examination of wall paintings to inform conservation and to understand painting techniques*" (**S8**). Furthermore, for the first time a researcher with an optics background has been recruited specifically to operate and conduct research using OCT (**S8**).

5. Sources to corroborate the impact (* participant in the process of impact delivery)

S1. Web-link: Smithsonian Magazine review https://www.smithsonianmag.com/smart-news/the-louvre-has-restored-st-john-baptist-180961037/
S2.* Testimonial letter: Director, Centre for Research and Restoration of the Museums of France
S3. Web-link: Fondation Beyeler and Nationale Suisse press release, 11 June 2020
S4. Testimonial e-mail: Chief Conservator, Beyeler Foundation
S5. Tate Gallery press release, 15 September 2014, https://www.tate.org.uk/press/press-releases/matisse-tates-most-successful-exhibition-ever
S6.* Testimonial letter: Senior Conservation Scientist, English Heritage
S7. Web-link: http://public.dha.ac.cn/content.aspx?id=528857548943, Dunhuang Academy
S8.* Testimonial letter: Deputy Director, Dunhuang Research Academy, Gansu Province, China
S9. Web-link: https://nature.altmetric.com/details/93963405/twitter
S10. Web-link: https://timesofindia.indiatimes.com/world/china/how-machine-learning-was-used-to-decode-an-ancient-chinese-cave/articleshow/79260772.cms, "How archaeologists decoded the origins of an ancient Chinese cave" The Times of India, Chandrima Banerjee, 21 Nov 2020,