Prognosis of Structural and Materials Health in Heritage Conservation

Roger M. Groves[1],

[1]*Aerospace Non-Destructive Testing Laboratory, Faculty of Aerospace Engineering,*
Delft University of Technology, Delft 2600 GB, The Netherlands

r.m.groves@tudleft.nl

ABSTRACT

Immovable 3D cultural heritage objects are an important part of the history and culture in Europe and provide a tangible connection with the past for current societies. These objects comprise religious buildings, castles and fortified buildings, palaces and historic houses, as well as engineering structures such as bridges and waterways. In many cases the buildings contain historic objects, including paintings, furniture, household items, as well as personal items such as jewellery and clothes. The structure of these buildings must be maintained to preserve both the building itself but also its contents. Cultural heritage objects are exposed to weather, changing climate, deterioration of materials, e.g. corrosion, moisture ingress, biological attack, pollution, wear and tear by use and sometimes vandalism. One of the challenges for heritage conservation is to combine the current detailed knowledge with an holistic approach to assessing the overall condition of the object. These parameters are necessarily subjective and comprise deterioration that causes a visual impact on the object, loss of function or loss of authenticity. This requires an interdisciplinary approach comprising the expertise of conservators, scientists, engineers and working in combination with stakeholders such as owners of heritage objects, local authorities and the public. This paper proposes the use of spatial referencing of chemical, biological and structural damage functions to enhance the prognosis capability in heritage science. The current situation is that these individual damage functions are either assessed separately or combined in an ad hoc way. The paper contains an example of immovable cultural heritage at risk in Europe, scientific approaches for the measurement and prognosis of chemical, biological, climate-related and structural damage, together with analysis tools to identify spatial regions with multiple degradation process indicators present.

1. INTRODUCTION

Cultural heritage objects are an important part of the history and culture in Europe and provide a tangible connection with the past for current societies (Lowenthal 1994). Immovable cultural heritage comprises religious buildings, castles and fortified buildings, palaces and historic houses, as well as engineering structures such as bridges and waterways. Immovable 3D cultural heritage is exposed to weather, changing climate, deterioration of materials, e.g. corrosion, moisture ingress, biological attack, pollution, wear and tear by use and sometimes vandalism (Caple 2000). A second category is movable cultural heritage objects, such as paintings, furniture, household items, as well as personal items such as jewellery and clothes. In the past many of these objects were moved to museums for display, however current trends are to display these objects in context in their original environment, and ideally in their original position. In this case historical objects are housed in historical building and structures and not only the structure of these buildings must be maintained to preserve the building itself, but the internal climate must be considered to preserve its contents.

Existing literature in conservation is heavily based on case studies, mainly for reasons of funding and project definitions, which are focused towards conserving individual or groups of objects for display. In Kos, Duin, Grevenstein, New, Young, Seymour, Groves and Horie (2014) a move was made away from this approach to consider the conservation of decorated wooden objects as a whole. Also taking an integrated approach is the Netherlands Institute for Conservation, Arts and Science (NICAS), which defines Material Dynamics as one of four research challenges[1] for transforming art history through science and technology (NICAS 2016). Material dynamics comprises chemical degradation processes and structural/mechanical changes in materials. At a higher level, the degradation processes can be considered to be

---

[1] The other three research challenges of NICAS are Science-enriched Art Historical Research, Conservation Dynamics and Diagnostics.

modified by interactions between different chemical and structural processes. First the degradation needs to be classified according to its cause, e.g. chemical-related, biological-related, climate-related and structural degradation. Subsequently degraded regions are mapped spatially and interactions between degradation processes interactions are studied.

This paper proposes the use of spatial referencing of chemical, biological and structural damage functions to enhance the prognosis capability in heritage science. The current situation is that these damage functions are either assessed separately or combined in an ad hoc way. The paper gives an example of cultural heritage at risk, then describes the degradation modelling and data mapping processes, then discusses the cross-interactions.

2. CULTURAL HERITAGE AT RISK

The purpose of this section is to give an example of cultural heritage at risk. St. George's Parish Church in Piran, Slovenia, is situated on top of the hill above the medieval city, see Figure 1. The church complex is composed of the parish church itself, the bell tower, the baptistery of St. John the Baptist and the priest's house. The complex follows a Venetian renaissance style and was developed gradually from the end of the 16th century up to the middle of the 17th century.

(a)

(b)

Figure 1. (a) View of the southern side of the church complex. (b) View of the east side of the interior with the high altar present at the end of the nave.

The church is situated close to the sea and is subject to both salt and moisture ingress from the maritime climate. Recent renovations have improved the condition of the buildings, as can be seen from the photos of the exterior and interior of the main church. Viewing the baptistery, the octagonal building on the right of Figure 1(a), reveals that the external plasterwork is subject to attack in the maritime climate, shown more clearly in Figure 2(a). Zooming in on the bronze statue of the Archangel Michael on the top of the bell tower, see Figure 1(a) and Figure 2(b), shows copper-bronze corrosion. Further the stonework below the statue shows additional damage as cracking and structural damage to the stonework and possibly biological attack also. Apart from the green appearance of the statue, the damage to the statue and stonework is not visible from the ground and extensive scaffolding would be needed to carry out an assessment of the conservation needs. Future deterioration to these objects could cause the loss of both structural and cultural details for future generations.

(a)

(b)

Figure 2. (a) View of the eastern side of the complex, with loss of plasterwork. (b) Close-up view of the bronze statue of Archangel Michael atop of the bell tower.

3. CHEMICAL-RELATED DETERIORATION

From the example in Section 2, it is clear that chemical degradation processes are important for materials conservation. Dose response functions for corrosion under European pollution conditions were developed in the EU project MULTI-ASSESS (Kucera 2005a), with corrosion of metals expressed as mass loss (ML, $g.m^{-2}$) for pollution parameters sulphur dioxide, nitric acid, ozone and particulates (e.g. PM_{10}) and climatic parameters temperature, rainfall, relative humidity and rain acidity. For both, copper and cast bronze the effect of relative humidity is introduced through the parameter RH_{60}. In coastal environments with pollution containing sulphate, chloride and nitrate ions, it was found that the rate of corrosion-induced copper runoff for new copper (1.5 $g.m^{-2}year^{-1}$) was significantly lower than the rate from corroded copper (19 $g.m^{-2}year^{-1}$) (Sandberg, Odnevall Wallinder, Leygraf & Le Bozec 2006). For atmospheric corrosion of quaternary bronzes a preferential dissolution of lead with respect to the other elements was identified. In terms of dissolution factor (f) the comparison can be expressed as: $f_{Pb} >> f_{Zn} >> f_{Cu}$, while no dissolved tin was found (Bernardi, Chiavari, Martini & Morselli 2008). Furthermore, many other papers describe the rate of corrosion processes on copper and bronzes (Zhang, He, Wallinder, Pan & Leygraf 2002; Watanabe, Toyoda, Handa, Ichino, Kuwaki, Higashi & Tanaka 2007; Bendezu, Goncalves, Neiva & De Melo 2007). In addition to these parameters chlorides are very active corrosion agents, as included in dose response functions developed by Tidblad (2005).

Water, in the form of precipitation or moisture penetrates porous materials and leads to the greater salt mobilization. Salts can originate from the building material itself, from salt-containing precipitations permeating through the surface or aerosol deposition (Bonn, Bertrand & Bonn 2009). Chemical weathering is a process where released cations: sodium, potassium, magnesium and calcium, form ionic crystals together with anions such as sulphate and chloride. During drying of wet stones, water evaporates and salt solutions become more saturated, eventually becoming supersaturated, exerting more and more pressure against the pore walls. The incidence of salt crystallisation depends on the pore structure of the building material, porosity, pore size distribution and pore shape, the saturation degree of the salt, the magnitude of the repelling force between the salt and the confining pore surface, and on the environmental conditions (Benavente, Linares-Fernandez, Cultrone & Sebastian 2006). One of the most destructive agents in porous masonry is sodium sulphate. This crystal can be present in anhydrous (anthenardite) or hydrous (mirabilite) forms. Hydrated crystals have a larger molecule volume than unhydrated ones and their growth can generate stresses in excess of the tensile strength of the stone and lead therefore to damage. Taking into account the complete saturation of the porous material with salt solution and assuming a tensile strength of 3 MPa for a typical building material, a pressure large enough to cause damage occurs in pores which are smaller than or equal to 70 nm in diameter. If the saturation is not complete, damage can occur in pores smaller than 20 nm in diameter (Rijniers 2004). Despite this it has been concluded that stones with a high porosity and a large percentage of small pores are more vulnerable to decay (Angeli, Bigas, Benavente, Menéndez, Hébert & David 2007).

4. BIOLOGICAL-RELATED DETERIORATION

Biological-related decay can cause chemical or structural degradation and may be due to bacteria, yeasts and fungi, plants and animals. Dose-response functions for mould growth on wood have been developed to estimate the evolution of the mould growth based on experimental data from tests performed on wood, allowing the risk of mould growth to be calculated and summed over time and the identification of a threshold value (Isaksson, Thelandersson, Ekstrand-Tobin & Johannson 2010). This function calculates a total daily dose (D), which is the product of two components, dependent upon the daily average temperature (T_d) and relative humidity (RH_d), $D = T_dRH_d$. In case of unfavourable condition, the daily dose can be negative, providing a setback for the germination process, but the accumulated daily dose can never be negative. A mathematical model for simulating mould growth on the surface of small wooden samples (pure pine and spruce sapwood) has also been developed for different climatic conditions of T and RH, simulating both indoor and outdoor (Hukka & Viitanem 1999). Developing a function for simulating fungal attack on outdoor wood allowed the quantification of a risk index of fungal growth, which is mainly dependent on temperature and moisture penetration due to precipitation. Brischke and Rapp (2008) monitored wood moisture content (MC_W), wood temperature (T_W) and the wood decay process over periods of up to 7 years, to determine dose-response relationships between climate factors and decay as a basis for the service life prediction of wood.

5. CLIMATE-RELATED DETERIORATION

The important role of sulphur and carbon compounds of anthropogenic origin has been widely demonstrated in surface soiling and black crust formation. The reaction of sulphur dioxide with carbonate materials leads to the formation of gypsum through the sulphation process, while elemental carbon (EC) in the aerosol is recognised for its role in soiling and blackening, and the ensuing aesthetic damage on monument surfaces (Sabbioni 2003; Brimblecombe & Grossi 2004). It should be pointed out that sulphur dioxide, while remaining an important damaging agent in the future, has already become less significant in the past 20 years, due to environmental legislation in the

EU. By contrast, fine carbonaceous particles rich in organic compounds emitted by vehicular traffic are gaining increasing importance in determining the future urban atmosphere, due to their expected influence on changing the colour of building facades towards yellowish-brown. These changes may arise from oxidation processes in the organic-rich deposits on facades, and can be a result of formation of compounds resembling humic substances (Sabbioni Brimblecombe & Cassar 2010). It is noted that some attempt to relate the rate of blackening to the amount of particulate matter in the air, while others assume that the particle loading is relatively constant over time, see Table 1.

Table 1. Damage functions related to soiling and blackening.

Function and Variables involved	**Reference**
$R_t=R_0-k(PM)^{0.5}$	(Beloin and Haynie 1975)
$R_t=R_0.\exp(-kt)$	(Watt & Hamilton 2003)
$R_t = R_0(R_0-R_p)[1-\exp(-kt)]$	(Brimblecombe & Grossi 2004)
$R_t=R_0.\exp(-ks.PM_{10.}t))$	(Kucera 2005b)
$-dR/dt =(R_0-R_p).VdEC.EC/\tau$	(Brimblecombe & Grossi 2009)

6. STRUCTURAL DETERIORATION

All materials and structures will degrade over time and eventually fail as a result of regular use (fatigue), corrosion, wear, ageing, and accidental damage. Furthermore, these processes are intimately linked to the starting conditions of the structure and variations in environmental conditions and usage. The condition and construction of the cultural heritage object is of great importance for the prediction of structural integrity problems. The starting point is condition reporting, performed by conservators surveying for collection management and conservation strategies which are well-established within the museum world (Cassar 1994).

Historically building have been unheated and some objects have survived surprisingly well in these conditions. It has also been found that that degraded objects can reach a very stable condition in historic houses as well as museums, despite climate conditions that do exceed the current climate specifications (Duin 2011). From the 1950s, uniformly heated spaces could be efficiently created by central heating, however, there was a collateral effect during the heating season: the relative humidity decreased significantly and the collection in the museum or historic house was exposed to dry air during several months. There are even stories of museum workers who could hear panel paintings ‘crack’ on very cold winter days. In order to reduce this risk of fracture due to an excessively low relative humidity, the air had to be humidified. Objects outdoors face additional structural challenges due to the variations in temperature, humidity, air quality and pollution. However as mentioned at the beginning of the paragraph ‘natural’ climatic changes are not necessarily bad for cultural heritage objects, as conditions are often slowly changing with the seasons.

Mecklenburg, Tumosa and Erhardt (1998) experimentally quantified the moisture response of materials in a panel painting to RH fluctuations. He used a painted panel composed of cottonwood, hide glue, gesso, and oil pain to assess the RH-related behaviour. Theoretically, the hide glue size was found to limit the allowable RH fluctuations of the panel most. However, because glue stresses relax over time, it was concluded that the glue influences the overall response of the panel only slightly. Kozłowski (2007) determined experimentally the critical levels of strain, above which damage in gesso appeared, as a function of a number of cycles of mechanical stretching to which specimens simulating historic panel paintings were subjected. A number of publications describe the modelling of moisture induced stresses using (multi-) Fickian diffusion processes (Rachwał, Bratasz, Łukomski & Kozłowski 2012); Dureisseix & Marcon 2011). Recent work includes the HERIe software (Działo, Bratasz, Kupczak, Kozłowski, Łukomski, Haber and Lasykhas 2016). Digital image correlation (DIC) combined with 3D finite element modelling was investigated by Dureisseix, Colmars, Baldit, Morestin and Maigre (2001). In the FP6 Multi-Encode Project (Moutsatsou, Kouloumpi, Olafsdottir, Trompeta, Tsaroucha, Doulgeridis, Groves & Tornari 2007; Thizy, Groves, Hatzigiannakis, Bernikola, Rochet, Hustinx, Pedrini, Tornari & Georges 2009), an holography/ shearography instrument for the full-field structural monitoring of movable cultural heritage was developed. As part of the project measurement procedures and image processing routines were developed to allow long term monitoring of artwork.

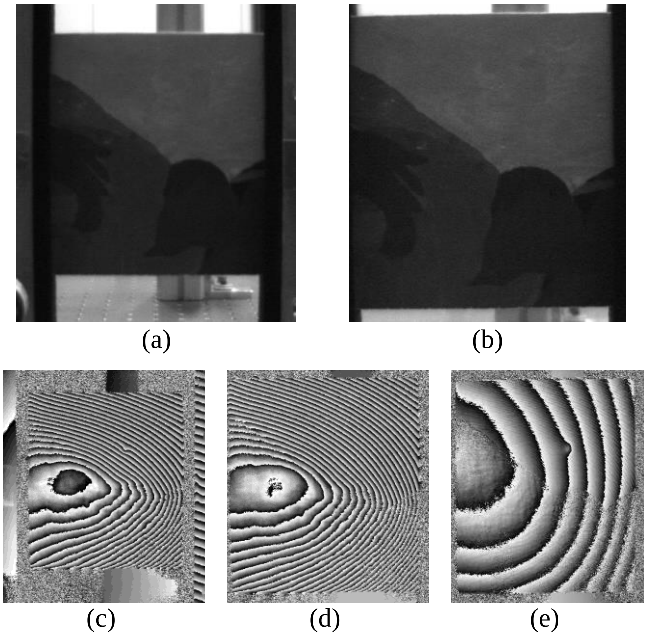
7. 3D DATA FUSION & VISUALISATION

This section briefly describes how 2D and 3D measurement data can be spatially registered to identify regions of interest for further investigation of material degradation mechanisms. In 2 dimensions the co-registration and interpolation procedure can be adapted from algorithms developed for SAR interferometry (Derauw & Roose 1995). These have recently been applied to cultural heritage structural diagnostics data by Groves, Thizy, Derauw, Alexeenko, Osten, Georges and Tornai (2009). An example of the image registration process is given below. These were co-registered using an affine transform according to Eq. (1) and Eq. (2):

$$x_2=A_x+B_x x_1+C_x y_1; \quad (1)$$

$$y_2=A_y+B_y x_1+C_y y_1 \quad (2)$$

where (x_1,y_1) and (x_2,y_2) are the image coordinates of the master and slave images, A_x, B_x, C_x, A_y, B_y, B_y are constants, determined by minimising the least squares error. Note in the co-registration process it is possible to correct for scaling differences between the phase maps. Figure 3(e) shows a new defect which is present just above the centre of the image.


(a) (b)

(c) (d) (e)

Figure 3. (a), (b) are camera views of a wooden panel painting mockup, recorded on different days. (c) is the master and (d) the slave interferograms recorded using digital holography with thermal loading, from these camera views. (e) is the co-registered phase image.

3D datasets can comprise point, line, area and volume elements, of different measurement parameter, e.g. surface, strain, spectral information. Interconversion between datatypes (point, line, area, volume) can be performed by interpolation, for example generating lines by connecting points and generating surfaces by connecting triangles. Registration of 3D data can be performed using different approaches. In Least Squares 3D Surface Matching (LS3D) (Gruen & Akca (2012), the parameters of the 3D-Helmert transform are determined by minimizing the Euclidian distance between meshed sections of the point clouds to be registered. Based on the SIFT operator developed by Lowe (2004), Scovanner, Saad and Mubarak (2007) extended the three-dimensional SIFT feature operator and Flitton, Breckon and Megherbi Bouallagu (2010) applied it to the detection of 3D features. Another approach is Iterative Closest Point (ICP) developed by Rusinkiewicz and Levoy (2001). This procedure estimates a spatial transformation of a random sample of a subset of the point cloud iteratively. These established registration methods are based on rather dense and low-noise 3D point clouds, which possibly also should be meshed. 3D digitisation in cultural heritage was performed by Guidi, Beraldin and Atzeni (2004), Guidi, Frischer and Spinetti (2005), Sitnik, Karaszewski, Zaluski and Bolewicki (2009). For virtual reality (VR) display Burdea and Coiffet (2003) describe that a further significant reduction in mesh size is required to allow interactive display within the memory requirements of standard PCs. Additionally texture and colour maps (spectral data) are introduced to improve the realism experienced by the user. The subsequent step is data fusion, the combination of data from different sensors, at possibly different spatial resolutions.

8. DISCUSSION

Spatial mapping of corrosion and hyperspectral imaging data is currently being performed in the NICAS Gilt Leather Project. Silver corrosion mapping was performed using Electrochemical Impedance Spectroscopy (EIS) by the group of Dr Arjan Mol, TU Delft. In parallel Dr Vassilis Papadakis, TU Delft has performed hyperspectral imaging (HSI). It should be noted that in the data fusion process EIS point measurements are mapped onto HSI surface measurements in this process. Further work is ongoing to investigate the spatial correlation between the datasets.

Among the many techniques described, the integration of cross-influences between the dose response functions is the main challenge. Based on the dimensionality of the data in terms of possible materials and structural elements and their interactions, a full determination using a multi-dimensional experimental or modelling approach would be too time consuming, even taking into account best practice in experimental design. The author has adopted the approach of spatial mapping of chemical and physical damage recorded using different measurement techniques, e.g. fibre optic sensing (Mizutani & Groves 2011), laser displacement sensing (Miesen, Sinke, Groves & Benedictus 2015), optical coherence tomography (Liu, Groves & Benedictus 2014), shearography (Anisimov & Groves 2015), spectral imaging (Papadakis, Müller, Hagenbeek, Sinke & Groves 2016) and ultrasonics (Ochôa, Infante, Silva & Groves 2015). Mapping is performed by the data fusion and image registration techniques described in Section 7. In regions where a clear correlation is determined by the mapping and classification algorithms (Papadakis 2016), the cross-influences between the dose response functions will be investigated in detail, over realistic chemical composition, environmental conditions and structural loading ranges.

9. CONCLUSION

This paper describes how cultural heritage is at risk of degradation from human and natural phenomena and gives a reminder that these objects are an important part of the history and culture in Europe. The degradation processes are complex and in this paper are considered from the perspective of chemical-related, biological-related, climate-related and structural degradation. The author describes his approach of mapping data from diverse sensor types and steps towards identifying spatial regions where the cross-influences between different degradation mechanisms will be of importance in gilt leather objects. Further work is ongoing to develop models of the cross-influences of the dose response functions for these materials. This paper proposes a new philosophy for prognosis of damage in heritage science using multi-sensor data fusion combined with spatial mapping of damage functions of chemical, biological and structural degradation.

ACKNOWLEDGEMENT

The research was partially supported by the Climate4Wood Project, the NICAS Gilt Leather Project and the NICAS Drawing out Rembrandt Project, funded by The Netherlands Organisation for Scientific Research (NWO). The case study example was provided by Dr. Polonca Ropret, Institute for the Protection of Cultural Heritage of Slovenia (IPCHS).

NOMENCLATURE

A_x, A_y	constants in affince transform
B_x, B_y	constants in affince transform
C_x, C_y	constants in affince transform
dR/dt	rate of change in reflectance
D	daily dose
DIC	digital image correlation
EC	elemental carbon concentration
EIS	electrochemical impedance spectroscopy
EU	European Union
f	dissolution factor
f_{Pb}	dissolution factor of lead
f_{Zn}	dissolution factor of zinc
f_{Cu}	dissolution factor of copper
HSI	hyperspectral imaging
ICP	iterative closest point
k	constant
ks	rate constant for blackening
LS3D	least squares 3D surface matching
MC_W	moisture content of wood
ML	mass loss
NICAS	Netherlands Institute for Conservation, Arts and Science
PM	particulate matter concentration
PM_{10}	particulate matter concentration of 10 $\mu g\ m^{-3}$
R	reflectance
R_t	reflectance after time t
R_0	initial value of reflectance
RH	relative humidity
RH_{60}	relative humidity of 60%
RH_d	average daily relative humidity
R_p	reflectance of surface covered by particles
SAR	synthetic aperature radar
SIFT	scale-invariant feature transform
t	time
T	temperature
T_d	average daily temperature
T_W	teperature of wood
VdEC	deposition velocity of elemental carbon
VR	virtual reality
(x_1,y_1)	pixel coordinates of master image
(x_2,y_2)	pixel coordinates of slave image
τ	folding density

REFERENCES

Angeli M., Bigas J.-P., Benavente D., Menéndez B., Hébert R. & David C. (2007). Salt crystallization in pores: quantification and estimation of damage. *Environmental Geology* 52, 205–213.

Anisimov, A. G. & Groves, R. M. (2015). 3D shearography with integrated structured light projection for strain inspection of curved objects. *Proceedings of SPIE* 9525, 952517.

Benavente, D., Linares-Fernandez, L., Cultrone, G. & Sebastian, E. (2006). Influence of microstructure on the resistance to salt crystallisation damage in brick. *Materials and Structures* 39, 105–113.

Bendezu, R. del P., Goncalves, R. P., Neiva, A. C. & De Melo, H. G. (2007). EIS and Microstructural characterization of artificial nitrate patina layers produced at room temperature on copper and bronze. *Journal of the Brazilian Chemical Society* 18, 54-64.

Beloin, N. R. & Haynie, F. H. (1975) Soiling of building materials. *Journal of the Air Pollution Control Association*, 25, 1946-1952.

Bernardi, E., Chiavari, C., Martini, C. & Morselli, L. (2008). The atmospheric corrosion of quaternary bronzes: An evaluation of the dissolution rate of the alloying elements. *Applied Physics*, A 92, 83–89

Bonn, N. S., Bertrand, F. & Bonn, D. (2009) *Damage due to salt crystallization in porous media*. http://arxiv.org/ftp/arxiv/papers/ 0906/0906.2502.pdf .

Brimblecombe, P. & Grossi, C. M.(2004). The rate of darkening of material surfaces. *Air Pollution and Cultural Heritage*, London: Balkema, 193-198.

Brimblecombe, P. & Grossi, C. M. (2009). Millennium-long damage to building materials in London. *Science of the Total Environment*, 407, 1354-1361.

Brischke, C. & Rapp, A. O. (2008). Dose–response relationships between wood moisture content, wood temperature and fungal decay determined for 23 European field test sites. *Wood Science and Technology*, 42, 507-518.

Burdea, G. C. & Coiffet, P. (2003). *Virtual Reality Technology*. Hoboken: John Wiley and Sons, Inc.

Caple, C. (2000). *Conservation Skills. Judgement, Method and Decision Making*. Abingdon: Routledge.

Cassar, M. (1994). *Environmental Management Guidelines for Museums and Galleries*. London: Routledge.

Derauw, D. & Roose, S. (1995). Co-registration and complex interpolation. *Proceedings of SPIE* 2584, 326-331.

Duin, P. H. J. C. van (2011). Panels in Furniture: Observations and Conservation Issues. *Facing the challenges of Panel Paintings Conservation, trends, treatments and training*. Los Angeles: The Getty Center.

Dureisseix, D., Colmars, J., Baldit, A., Morestin, F. & Maigre, H. (2011). Follow-up of a panel restoration procedure through image correlation and finite element modelling. *International Journal of Solids and Structures*, 48, 1024–1033.

Dureisseix, D. & Marcon, B. (2011). A partitioning strategy for the coupled hygromechanical analysis with application to wood structures of cultural heritage. *International Journal for Numerical Methods in Engineering*, 88: 228–256.

Działo, A., Bratasz, L., Kupczak, A., Kozłowski, R., Łukomski, M., Haber, J., Lasykhas, L. (2016) *HERIe software*. www.herie.mnk.pl, accessed 14th March 2016.

Flitton, G., Breckon, T. & Megherbi Bouallagu, N. (2010). Object Recognition using 3D SIFT in Complex CT Volumes. *Proceedings of the British Machine Vision Conference*, S. 11.1-11.12, BMVA Press.

Groves, R. M., Thizy, C., Derauw, D., Alexeenko, I., Osten, W., Georges, M. & Tornai, V. (2009). Automated phase map referencing against historic phase map data. *Proceedings of FRINGE'09*, Stuttgart.

Gruen, A. & Akca, D. (2012). Least Squares 3D Surface Matching. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Bd. XXXIV.

Guidi, G., Beraldin, J.-A. & Atzeni, C. (2004) High accuracy 3D modelling of Cultural Heritage: the digitizing of Donatello's Maddalena. *IEEE Transactions on Image Processing*, 13(3), 370-380.

Guidi, G., Frischer, B. & Spinetti, A. (2005). 3D digitisation of a large model of imperial Rome. *Proceedings of the 5th International Conference on 3-D Digital Imaging and Modeling (3DIM'05)*, 1550-6185.

Hukka, A. & Viitanem, H.A. (1999). A mathematical model of mould growth on wooden material. *Wood Science and Technology*, 33, 475-485.

Isaksson, T., Thelandersson, S., Ekstrand-Tobin, A. & Johannson (2010). Critical conditions for onset of mould growth under varying climate conditions. *Building and Environment* 45, 1712-1721

Kozlowski, R. (2007). Climate induced damage of wood: numerical modelling and direct tracing. *Experts Roundtable on Sustainable Climate Management Strategies*, Los Angeles: The Getty Conservation Institute.

Kos, N., Duin, P. van, Grevenstein, A. van, New, B., Young, C., Seymour, K., Groves, R.M. & Horie, V. (2014). The conservation of panel paintings and related objects. The Hague: Netherlands Organisation for Scientific Research (NWO).

Kucera, V. (2005a) EU FP5 RTD Project Model for multi-pollutant impact and assessment of threshold levels for cultural heritage. *Publishable Final Report*, contract no. EVK4-CT-2001-00044.

Kucera, V. (2005b). Model for multipollutant impact and assessment of threshold levels for cultural heritage. *Internal Report*. Stockholm: Swedish Corrosion Institute.

Liu, P., Groves, R. M. & Benedictus, R. (2014). 3D monitoring of delamination growth in a wind turbine blade composite using Optical Coherence Tomography. *NDT & E International*, 64, 52–58.

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

Lowenthal, D. (1994). The value of age and decay. In Krumbein, W. E., Brimblecombe, P. & Cosgrove, D. E. (eds). *Durability and Change*, Chichester: Wiley.

Mecklenburg, M. F., Tumosa, C. S. & Erhardt, D. (1998). Structural Response of Painted Wood Surfaces to Changes in Ambient Relative Humidity. *Painted wood: history and conservation (Part 6: Scientific Research)*. Los Angeles: The Getty Conservation Institute , 464-483.

Miesen, N., Sinke, J., Groves, R. M. & Benedictus, R., (2016). Laser displacement sensing for flaw detection during pre-preg CFRP production. *The International Journal of Advanced Manufacturing Technology*, 82, 1, 341-349.

Mizutani, Y. & Groves, R. M. (2011). Multi-Functional Measurement Using a Single FBG Sensor, Determination of strain, bending moment and vibration frequency from a single fibre Bragg grating. *Experimental Mechanics*, 51, 1489-1498.

Moutsatsou, A.P., Kouloumpi, E., Olafsdottir, J., Trompeta, M., Tsaroucha, C., Doulgeridis, M., Groves, R.M. & Tornari, V (2007/2009). Protocols for the construction and characterization of model panel paintings for the evaluation of structural diagnostic techniques, *Proceedings of Wood Science for Conservation of Cultural Heritage*, 105, Florence: Firenze University Press.

Netherlands Institute for Conservation, Arts and Science (NICAS) (2016), www.http://www.nicas-research.nl, accessed 14th March 2016

Ochôa, P., Infante, V., Silva, J. M. & Groves, R. M. (2015). Detection of multiple low-energy impact damage in composite plates using Lamb wave techniques. *Composites Part B: Engineering*, 80, 291–298.

Papadakis, V. (2016). *TU Delft Image Processing Platform*. http://www.lr.tudelft.nl/tipp, accessed 22nd February 2016.

Papadakis, V. M., Müller, B., Hagenbeek, M., Sinke, J. & Groves, R. M. (2016). Monitoring chemical degradation of glass fibre composites using hyper-spectral imaging, to be presented at SPIE Smart Structures NDE, Las Vegas, March 2016.

Rachwał, B., Bratasz, Ł., Łukomski, M. & Kozłowski, R. (2012). Response of Wood Supports in Panel Paintings Subjected to Changing Climate Conditions. *Strain*, 48, 366–374.

Rijniers, L. A. (2004). *Salt crystallization in porous materials: an NMR study*. Technische Universiteit Eindhoven, 9–23.

Rusinkiewicz, S. & Levoy, M. (2001). Efficient Variants of the ICP Algorithm. *Third International Conference on 3D-Digital Imaging and Modeling (3DIM)*.

Sabbioni, C. (2003). Mechanisms of air pollution damage to stone. *Effects of Air Pollution on the Built Environment*, 63-106, Singapore: Imperial College Press.

Sabbioni, C., Brimblecombe, P. & Cassar, M. (2016). Atlas of climate change impact on European Cultural Heritage, 146. London: Anthem Press.

Sandberg, J., Odnevall Wallinder I., Leygraf C. & Le Bozec N. (2006). Corrosion-induced copper runoff from naturally and pre-patinated copper in a marine environment. *Corrosion Science*, 48, 4316–4338.

Scovanner, P., Saad, A., Mubarak, S. (2007). A 3-dimensional sift descriptor and its application to action recognition. *Proceedings of the 15th International Conference on Multimedia*, Augsburg, Germany.

Sitnik, R., Karaszewski, M., Zaluski, W. & Bolewicki, P. (2009). Automated full-3D shape measurement of cultural heritage objects. *Proceedings of SPIE* 7391, 73910K.

Thizy, C., Groves, R. M., Hatzigiannakis, K., Bernikola, E., Rochet, J., Hustinx, G.-M., Pedrini, G., Tornari, V. & Georges M. (2009). Le projet MULTIENCODE: développement d'un multisenseur holographique pour la détection des signatures des œuvres d'art mobiles, *CMOI2009*, Reims.

Tidblad J. (2005) Deliverable 2, EU project Noahs Ark (SSPI-CT-2003-501837).

Watanabe M., Toyoda E., Handa T., Ichino T., Kuwaki N., Higashi Y. & Tanaka T. (2007). Evolution of patinas on copper exposed in a suburban area, *Corrosion Science*, 9, 766-780.

Watt, J. & Hamilton, R. (2003). The soiling of buildings by air pollution. *Effects of Air Pollution on the Built Environment*. Singapore: Imperial College Press.

Zhang X., He W., Wallinder I. O., Pan, J. & Leygraf C. (2002), Determination of instantaneous corrosion rates and runoff rates of copper from naturally patinated copper during continuous rain events, *Corrosion Science* 44, 2131-2151.

BIOGRAPHY

Roger M. Groves is from Bridgwater, UK and has a BSc in Chemistry from the University of Wales, Aberystwyth (1988), an MSc in Applied Physics with distinction from the University of Hertfordshire, Hatfield, UK (1997) and a PhD in Optical Engineering from the School of Mechanical Engineering, Cranfield University, UK (2002). From 2001-2005, he was a Research Fellow in NDT/SHM of helicopter rotor blades at Cranfield University and from 2005-2008, he was a Senior Scientist in NDT/optical metrology of artwork at the Institut für Technische Optik, University of Stuttgart, Germany. In 2008, he was appointed Assistant Professor in the Faculty of Aerospace Engineering, Delft University of Technology, The Netherlands, where he is Head of the Aerospace NDT Laboratory, a research laboratory on NDT/SHM technology and applications. He has more than 100 publications in NDT, SHM, optical metrology and ultrasonics in the application fields of aerospace engineering and cultural heritage. He is a Senior Member of SPIE, Member of OSA, Member of the IOP, UK and Member of the RSC, UK. He is CPhys (IOP) and CSci (RSC) and in 2002 his PhD thesis was shortlisted for King's Norton prize for the best PhD thesis at Cranfield University.