Autonomous Near-Field Communication (NFC) Sensors for Long-Term Preventive Care of Fine Art Objects

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Keywords: wireless sensor; near-field communication (NFC); preventive care; microclimate; panel painting; cultural heritage

Highlights:

- Design of NFC sensor-tags for logging temperature, relative humidity and light
- Tags attached on inside and outside of microclimate enclosure read by smartphone
- Continuous *object-level* monitoring of a C16th panel painting sealed within enclosure
- Six month *in-situ* pilot study with painting hanging in a real, uncontrolled climate
- Detailed analytics of microenvironment enclosure performance from sensor data

Abstract

We present the design and pilot trial of near-field communication (NFC) sensors for the long-term preventive care of fine art objects. This work was undertaken to address the unmet need for a permanent and unified *object specific* sensory and digital data labelling system for fine art objects that does not require large-scale wireless infrastructure. The sensor-tags are demonstrated in a six-month pilot study to evaluate the temperature and humidity buffering performance of a microclimate enclosure (MCE) constructed to protect a late C16th panel painting. The framed painting fitted with NFC sensor-tags was hung in a busy, and environmentally uncontrolled, Cambridge college dining hall to mimic a typically large, semi-public exhibition space. The resulting visibility of climatic conditions and the detailed analytics made possible from the data sets harvested from the NFC sensor-tags have provided invaluable information to the painting conservators. This study provides the first steps in

understanding how *object specific* electronic sensor-tags will play a critical role in improving the display management, storage and long-term preventive care of fine art objects.

Introduction

Museum institutions as keepers of fragile cultural objects face a paradox. They are duty-bound to preserve these objects – often in their thousands, yet also duty-bound to exhibit and display them. How then to best address the challenge of the preservation of cultural objects in their care, whilst simultaneously exposing them to the inherent risks of storage, exhibition and touring? There is no single or simple answer to the paradox, but there is an opportunity for *object specific* labelling with smart NFC/RFID sensor-tags that combine environmental sensing with asset management records on a single platform. Smart NFC-sensor-tags can provide insight and visibility on an object's status, can log the environmental conditions experienced by each object, and can support the long-term conservation and institutional management of cultural heritage and fine art objects. This paradigm is illustrated conceptually, Fig.1, where digital data and object status monitoring are combined on a single electronic NFC sensor-tag.

Near-field communication (NFC) and radio-frequency identification (RFID) tags provide instant access to an individual object's digital data. Electronic tags have variously been used by cultural institutions for inventory management [1], authentication and provenance [2] and for enhancing visitor experience within galleries [3]. In this work, the integration of environmental sensors onto digital asset tags provides additional information on the condition status of an art object and provides an electronic record of its environmental exposure. These novel, autonomous, low-energy NFC-enabled sensor-tags could therefore support museum work-flow around collections management, display and storage condition monitoring, packing, moving and tour management, as well as general record keeping on a single *unified* technology platform.

The functional unification of asset data with sensing is not easily achievable with any alternative mainstream wireless sensor network or tag technology available today. For example, optical barcodes and QR labels can provide a low-cost solution to museum inventory management [4], but these paper-based labels rarely contain any data about the object itself – they are signposts to where the data is *actually* stored, most usually an institutional database – neither can they sense nor monitor the environment of the object. Sensing is a prerequisite that should underpin all long-term preventive care, display and storage strategies for priceless fine art objects. Electronic Bluetooth sensor beacons consume too much energy for consideration as digital asset labels, since many years of maintenance-free operation is required once an item has been tagged. ZigBee sensory nodes require supporting wireless infrastructure - a local network receiver or master node - making them less attractive for tagging art objects that may frequently move about within an institution, or that regularly go out on tour or loan. Moreover, the ZigBee radio protocol is not currently supported on mobile consumer products such as tablets, laptops or smartphones, which presents a serious barrier to widespread adoption. A proprietary indoor microenvironment art monitoring system with good battery life was reported some years ago, although this wireless system was also not - at the time of publication - compatible with any standard consumer devices [5].

The objective of this work has therefore been to address the unmet need for a unified and *object specific* sensory and digital data labelling system for fine art objects that does not require significant wireless infrastructure. Specifically, the NFC sensor-tags developed here have, amongst other trials, been used in a case study to evaluate the temperature and humidity buffering performance of a microclimate enclosure (MCE) constructed to protect a late C16th panel painting hung in a busy, and environmentally uncontrolled, Cambridge college dining hall. This study provides the first step in understanding how *object specific* sensor-tags will play a critical role in improving the display management, storage and long-term preventive care of fine art objects.

Background

Sixteenth century wooden painting supports are inherently sensitive to fluctuating relative humidity (RH), due to the hygroscopic nature of the material [6, 7]. The thin chalk or gesso grounds and paint layers typical of this type of painting have very limited elasticity however, and they are therefore prone to delaminate if the support is cycled through fluctuating RH, because they cannot accommodate the often visibly evident dimensional changes of the support, *i.e.* increased convex curvature across the panel face during a dry spell, and flattening out in higher RH [8, 9]. While past restorers have attempted to restrict this movement by attaching rigid cradles to the backs of panel paintings, we now know that this can be equally detrimental, and conservators today are therefore looking to implement preventive measures to reduce environmental impact. It is also a fact that the composite structure of a panel painting is more vulnerable to rapid environmental changes than to slow ones [8], which is one of the explanations why many works of art in churches survived relatively well for centuries of consistent but slow annual cycles, while the introduction of modern heating, ventilation and air conditioning (HVAC) systems has caused rapid deterioration [10, 11].

The idea of protecting works of art by exhibiting them in sealed environments is not new, and countless microclimate enclosures, with or without buffers, have been constructed over more than a century. A microclimate enclosure was made for a J.M.W. Turner painting as early as 1892 at the Victoria and Albert Museum, London [12]. Although a sealed environment is typically the aim, it is, in reality, near impossible to achieve a perfect enclosure. In spaces with uncontrolled and frequent environmental fluctuations, such as a busy, historic dining hall with an old-fashioned heating system and a frequent influx of people, the historic portraits adorning the walls are particularly vulnerable [13]. Previous research has shown that even a very successfully sealed frame or case, when placed in an environment differing from the internal one, will equilibrate over time, and this is part of the reason why sealed exhibition cases or frames are used predominantly as a temporary measure, for example during loans, when the external conditions become harder to control and potentially more volatile over a limited period [14]. If a buffered microclimate is desirable over longer periods however, it must be re-calibrated at regular intervals, but this may nevertheless be the best option, if changing the environmental conditions of an exhibition space is not achievable [11].

The challenge of integrating inventory and asset management data together with *object specific* environmental condition sensing can be addressed with low-power sensor-tag technology. Our approach to this challenge has been to develop low-energy autonomous sensor-tags that support museum work-flow across collections management, display and storage condition monitoring, packing, moving and tour management, and general record keeping on a *unified* NFC technology platform. In this work we demonstrate the benefits of this technology for display and storage condition monitoring in conservation and preventive care.

Materials and Methods

NFC Sensor-tag

A low-energy NFC sensor-tag was designed around the SL13A integrated circuit from Austria Microsystems AG (since superseded by the AS39513), Fig.2(a). This is an NFC type 5 tag, based on the ISO15693 standard, and a data logger in a single integrated circuit. A precision low-power integrated circuit temperature and RH sensor, CHIPCAP-R, from GE Measurement & Control Solutions Inc provided the sensing capability. The tag electronics was rationally designed and laid out on a multi-layer surface-mount FR4 printed circuit board (60 x 60 x 15 mm, weight including coin cell 13g) with a planar loop antenna for the NFC link, Fig.2(b)-(c). A batch of 40 NFC sensor-tags was manufactured at RAK Printed Circuit Boards Ltd for the Hamilton Kerr Institute.

NFC Sensor-tag Energy Model

During the electronics design process a state-based energy model was created for the NFC sensor-tags to estimate average power consumption. The model treats the tag as a state machine that loops through a series of known states. The duration and typical operating current of each state were taken from manufacturers' data sheets. The operational states accounted for by the model are: Sample Acquisition, Write to Memory, and Sleep. These have a duration respectively of t_{ac}, t_{wr} and t_{sp}. In each state a current is drawn from the battery denoted by i_{ac}, i_{wr} and i_{sp}. The electric charge required in each state is calculated as the sum $i_n.t_n$, and this determines the overall battery discharge rate. The model supports variable inputs for battery capacity, battery self-discharge rate, memory access speed and write time, and the duration of the standby period. The model generates graphical outputs in the form of charts, plotting average current consumption *vs*. sample period, Fig.3(a), and the battery lifetime *vs*. sample period, Fig.3(b), based on the input variables.

Microclimate Enclosure

For the case study reported here, a sealed frame-environment to buffer the panel from the uncontrolled dining hall environment was created as follows. The frame rebate was lined with foil-back sealing tape, the glazing dropped in, and a neutral moisture curing non-corrosive silicone bead applied to seal in the glass. The panel was dropped in onto fitted wooden profiles cut to the curvature of the panel at 50 %RH and secured in place without cross-grain restraining of the panel edges. Neoprene closed pore foam strips supplied a gasket seal against the frame back for the foam core backboard, which was given an inner MarvelSeal® (aluminised polyethylene and nylon barrier) backing. A Melinex®-covered window (archival polyester film) was cut and an NFC sensor-tag mounted to the inside, Fig.2(d) – (e). A second NFC sensor-tag was mounted externally.

Pilot Study and Protocol

This pilot study was initiated after an earlier failure of the same MCE seal due to delamination of the sealing tape along the bottom section. This type of failure is unprecedented, and warm air from heating elements under the seat below the painting is the most probable cause, although without environmental data, this hypothesis could not be confirmed. The monitoring was therefore set up to better understand the conditions in which the painting hangs and to confirm the performance of the MCE, once it had been resealed. NFC sensor-tags were programmed to measure temperature and RH at a rate of 1 sample every 30 minutes using the AS3911 development kit from Austria Microsystems AG. During and after the pilot study, logged data was read out from the tags with an NFC smartphone application, *e-Tag Reader,* from GoSense Wireless Ltd, and stored in comma separated value (.csv) files for import into MS-Excel.

Numerical Methods

Absolute humidity (AH) values were computed in MS-Excel from the measured RH and temperature data by calculating the water vapour saturation pressure, P_{ws}, at each sample point [15] and computing AH from the relation

$$AH = C.\ P_{ws}/T \qquad (1)$$

where C = 2.16679 gK/J, P_{ws} is the water vapour saturation pressure in Pa, and T the temperature in K. Time-series plots of temperature, RH and AH were generated in Excel, Fig.4, and scatter plots generated of RH *vs.* temperature, Fig.5.

An uncertainty error analysis was performed on the forward analogue sensor signal path by combining the instrumental limit of error (ILE) of each component in order to estimate the final accuracy of measured sensor data, Table 2 [16].

Results

Tag operating current and battery lifetime estimation models

The time averaged current demand *vs*. sample period of the NFC sensor-tag was computed by the state model, and is shown as a log-log graph, Fig.3(a). The stacked bars of the figure illustrate the individual contribution of each state to the total current demand at the given sampling period. As the sampling period decreases, the relative current demands of Sample Acquisition and Write to Memory become dominant. As sampling period increases the relative contribution of Sample Acquisition and Write to Memory - which are of fixed duration - diminish, and the average current demand of the tag tends towards the Sleep value of approximately 3.5 µA. For all sample periods > 0.03 hr (equivalent to a sample rate of about 2 samples per minute) the average current drain is less than 10 µA at a supply voltage of 5V, or an average power consumption of under 50 µW. At 1 S/hr the average power consumption of a tag approaches 18 µW. Parsing this data to the battery model results in the battery lifetime estimate, Fig.3(b). This is based on manufacturers published data for a Varta CR2032 3V lithium manganese dioxide coin cell operating at 25 °C. The battery life estimate, accounting for battery self-discharge of 1 %/yr is 80 months at a sample rate of 1 S/hr, or about 6.6 years. The storage life of the Varta CR2032 is typically 10 years or better in temperate environmental conditions.

T, RH and AH inside and outside the MCE

The recorded temperature and relative humidity values and the computed values of absolute humidity from outside and within the MC enclosure for the six-month period December 2016 to June 2017 are shown, Fig.4. The measured T and RH data is also plotted as a scatter graph to illustrate the distribution over the course of the pilot study, Fig.5. It is evident from the time-series data and scatter plots that the MCE provides significant buffering of the panel painting against RH fluctuations but offers little or no buffering against ambient temperature fluctuations. This data is summarised in Table 1.

Table 1. Tabulated performance metrics of the microenvironment enclosure

Period *12/16 – 06/17*	T_{ext} / °C	T_{int} / °C	ΔT / °C	RH_{ext} / %	RH_{int} / %	ΔRH / %
Max.	29.1	30.7	**1.6**	78.5	86.8	**8.3**
Min.	10.8	11.1	**0.3**	21.8	50.3	**28.5**
Mean	16.8	17.1	**0.3**	51.3	55.5	**4.2**
S.D.	3.4	3.4	**0.0**	8.6	2.6	**-6.0**

T and RH measurement error analysis

The error analysis accounts for systematic errors present in the forward signal path of the analogue sensor system, Table 2. The systematic sources of error are taken as the instrument limit of error (ILE) and/or least count for each component in the forward signal path comprising the sensor, the sensor preamplifier and the analogue to digital converter (ADC).

Table 2. Tabulated systematic error analysis based on the ILE of the forward signal path

	Instrument Limit of Error (ILE)* *Under conditions 10 < T < 55 °C and 0 < RH < 90 %			
	T&RH Sensor error	Preamplifier error / ±%	ADC Precision / (1/ENOB) x 100%	Total estimated uncertainty
Temperature	±0.4 °C max.	12 max.	0.40 max	±4.5 °C max.
	±0.3 °C typ.	2 typ.	0.10 typ	±1.0 °C typ.
Relative Humidity	±2.5 % max.	12 max.	0.40 max	±5.6 % RH max.

	±2.0 % typ.	2 typ.	0.10 typ	±2.5 % RH typ.

The estimated uncertainties computed from the composite ILEs in the forward signal path are temperature ±4.5 °C max. and ±1.0 °C typical, and humidity ±5.6 % RH max. and ±2.5 % RH typical. Random errors were not included in the analysis as they are most likely to arise from short-lived electrical noise events in the analogue front end that are difficult to predict. The data sampling system employs an averaging technique that minimises the impact of random noise events. Random digital bit errors arising during file transfers are handled by the ISO15693 protocol.

Discussion

In the past decade there has been significant research carried out on embedding physical and chemical sensors into RFID and NFC tags. Several detailed reviews have covered this field of research [17-19]. Some of the most interesting work on quantitative sensing with RFID and NFC tags was performed by Steinberg and Steinberg, and may be traced back to their original research article describing an optoelectronic interface implemented on a passive RFID tag for chemical detection of pH [20]. More recently, as the demand for environmental sensing through the cold-chain and logistics supply-chains has grown, research on integrating physical sensors onto tags, especially for temperature and humidity, has expanded [21]. Intel Research in collaboration with several universities has been pioneering its open source wireless identification and sensing platform (WISP) for mobile computing and IoT applications across several wireless standards. WISP includes an NFC platform that has been used for temperature, humidity and motion sensing [22]. With recent moves toward low-cost roll-to-roll printing of RFID tags aided by the plastic electronics revolution, focus has also turned to the printed manufacture of multi-sensor RFID tags [23], specifically targeted for use in environmental sensing applications [24].

Most art museums and galleries monitor their indoor exhibition spaces for temperature and humidity as standard practice. Typically, this is achieved in larger institutions with permanent mains-powered data loggers installed at discrete locations, with wireless data transfer direct to the institutional Wi-Fi network or via 866 MHz radio transceivers arranged at appropriate locations. There are several commercial vendors of such systems. Alternative wireless systems have been researched for simple and more rapid deployment at both indoor and outdoor cultural sites [25, 26]. Many museum environmental monitoring systems now include air pollution and air quality sensors in addition to temperature and relative humidity [25, 27]. We have previously developed and reported different mobile chemical sensors for general environmental monitoring, including for pH, ions and ethanol vapour [20, 28-32].

To extend the spatial resolution and relevance of environmental data to a specific art object however requires monitoring the object's microclimate rather than the general room climate. This more targeted approach has been demonstrated in a cathedral vault containing fresco paintings [33]. In almost all cases, considerable effort and cost are entailed in the installation of permanently wired or multi-node wireless systems. Simple low-cost peak humidity indicators based on anodic oxidation have been researched that could be attached to individual pieces of art [34]. And passive ultra-high frequency (UHF) RFID humidity sensor-tags specifically developed for integration into wood products could in principle be incorporated into painting frames or onto panel paintings [35]. However, these very low-cost solutions do not provide data logging, nor store an object's environmental exposure history, nor temperature data nor any digital object (inventory) data. A considerably more sophisticated modular 'plug-and-play' environmental sensor solution based on RFID technology has recently been reported by a museum in Hong Kong [36].

Thus, we believe the NFC sensor-tag system developed here optimises the various requirements surrounding ease of use, low installation cost, as well as unification of asset management data with *object-level* environmental monitoring on a single technology platform.

Performance of the NFC sensor-tags

In a separate study the NFC-sensor-tags were found to return accurate T and RH data compared to a calibrated Hanwell Synergy system in a museum gallery environment [37]. Here the sensor-tags provided 10-bit data precision with a typical overall accuracy of better than ±1.5 ºC in the range 10 – 55 ºC and ±3% RH in the range 20 – 80 %RH, in agreement with the ILE uncertainty figures, Table 2. In this present pilot, tags were operated continuously from Dec 2016 to June 2017, and again from August 2017 to October 2017 at a logging rate of 2 samples/hr without battery change. Accelerated aging tests are now required to confirm the 6.6-year battery life estimate predicted by the state-model. The NFC-sensor tags contain a contactless charging circuit that allows the battery to recharge through the near-field interface. To implement wireless recharging the battery must be rechargeable, typically a Li-Al alloy-manganese dioxide type such as the Maxell ML2032. This battery type has a lower capacity (65 mAh) compared to the Varta (230 mAh). So under similar load conditions and without recharge, this battery would only power a tag for approximately ¼ the length of time. This fact should be considered prior to any installation. It is also feasible to recharge the NFC-sensor tags via alternative energy sources, including photovoltaic cells. In practice, connection to photovoltaic cells for harvesting light energy is not very simple in a typical museum setting since tags will usually be hidden out of sight when attached to art work, or be embedded in picture frames, or enclosed in transport flight cases. Again, the specific installation should be considered and an appropriate decision can then be taken on that basis.

The ISO15693 tag type 5 NFC protocol supports wireless data transfer at 26 kbps. Data is exchanged in frames with a start-of-frame header, optional 64-bit tag identification code, 16-bit instruction, 8-bit data, 16-bit CRC and an end-of-frame marker. We found in practice that allowing for all necessary handshaking and CRCs exchanged between tags and a midrange quality NFC-enabled Smartphone (Lenovo P2) that logged data could be down-loaded from a tag at an effective rate of 26 sets of 16-bit T, RH and timestamp data per second. In other words, 6-months of logger data acquired at 2 samples/hr comprising 8760 samples of T, RH and timestamp data – altogether 26280 16-bit values - takes 337 s, or 5.5 minutes, to transfer to the smartphone. For a painting or work of art inspected annually, this equates to a download time of 11 minutes, during which time the conservator or curator can perform the condition check. To prevent interruptions and premature termination of downloads during long file reads, the e-Tag Reader Android application does not terminate the current session if the phone and tag loose contact. The application monitors which tag it has started a transfer with - using the tag Unique ID - and it will not collect data from any other tag should one enter the field until the first transfer is completed. The application will also continue an original download from the address at which it left off if there is any break in the contactless connection during a file exchange. These features ensure robust file transfer to the ‘phone.

Performance of the MCE

The mean temperature inside the MCE is 0.3 °C higher than mean ambient temperature, but there is no difference in the standard deviations of the internal and external temperatures, Table 1. Mean relative humidity inside the MCE is 4.2 % higher than ambient, but the standard deviation about the mean is 6.0 % less, indicating the highly favourable buffering performance of the MCE against RH swings. The MCE does not protect or buffer the painting against ambient temperature changes, which is unsurprising, as this was not a design goal for this frame.

Observable events in time-series data

Transient events (spikes) in the humidity level inside the MCE occurred on several occasions, most notably in the period mid-March to mid-April 2017 and again mid-May to June, Fig.4(b). Upon closer inspection, these positive-going spikes in the MCE’s internal humidity appear to occur where there is a sudden increase in ambient temperature which also causes the ambient RH around the frame to drop, Fig.6. We attribute these sudden temperature rises to solar gain from incident sunlight falling on the glazed painting. In the absence of these rises in ambient temperature, internal transients in RH are small or non-existent. The rising and falling edges of the RH transients can exceed rates of ±20%/hr, although they are generally short lived at under 2 hours. It is not thought that panel paintings are susceptible to damage by such fast and short RH transients, but this might warrant further investigation [38]. It is interesting to note that, in general, the relative humidity changes inside the MCE are in the opposite direction (i.e. out of phase) with the changes in ambient relative humidity, Fig.6(b).

To isolate the origin of the sudden late afternoon ambient temperature rises measured around the MCE a third NFC-sensor-tag was deployed to measure incident UV/Vis light level with a broadband photodiode detector, type SFH206K from Osram Optosemiconductors. We believed the temperature increases were due to incident sunlight from large, west-facing windows opposite the painting. The light sensing tag was operational from early July to the start of October 2017, together with both the internal and external MCE tags. Inspection of the light and temperature data confirmed that afternoon light incident upon the MCE was causing the temperature rises and the ensuing relative humidity transients, Fig.7.

Impact on preventive care

Over a period of almost 10 months, it is evident that despite the extreme fluctuations in the external environment, the RH within the enclosure did not drop below 50%, Fig.5(b), Table 1. As expected, the external conditions were anything but ideal, and the regular solar gain induced heating cycles that cause the panel painting to release moisture to equilibrate the small volume of air surrounding it are not desirable. However, recent studies by the National Gallery, London, have shown that with an air volume no bigger than that present in this type of sealed frame environment, the amount of moisture released by the panel when the MCE heats up is in fact minimal [39], and much less than if it had been attempting to buffer the entire dining hall environment. The NFC sensor-tags clearly confirm the desired performance characteristics of the MCE and provide detailed insight into the actual microclimate experienced by the panel painting.

From a long-term conservation strategy perspective, this trial shows how the performance of an MCE can be tested against external conditions in a straight-forward manner, without the need to reopen the enclosure or bring specialist data logging equipment to a busy exhibition site. This is clearly an advantage for private clients, large institutions and the visiting public who are thus less inconvenienced by intrusive and unsightly monitoring equipment that can easily disrupt the aesthetic of an exhibition or piece of art. Importantly, it means long term preventive care strategies for specific works of art can be planned and monitored and their compliance verified using the same platform that is used for object inventory. Indeed, as shown here in this pilot study, it has been easy to modify the trial to check a hypothesis – *i.e.* whether sunlight was the cause of the humidity transients, by installing the light sensing tag. Furthermore, in using this unified system during an annual condition check, a conservator has all recent microclimate exposure data for the object at their fingertips, which can help them identify the root cause of observable damage or deterioration. With the possibility of aggregating data to the institutional database, Fig.1., it is evident that a full historic picture can be built up for every individual work of art that is tagged in this way, and the impact of any passive or active environmental control measures can be monitored and suitably adjusted according to their success in improving the ambient conditions of an exhibition space. In the case of the Trinity College dining hall, a simple solution for reducing the rapid, heat-induced changes occurring within the MCE, would be to install curtains to be drawn before the relevant window during sunny afternoons. The narrow time frame during which this measure would be relevant can be very precisely deduced from the collected data. Another option would be the installation of UV filter film on the windows, which could reduce solar induced heat gain by up to 60%. However, any solution would need to be weighed up against other priorities for this historical setting, and arguably, the data in this instance shows that the microclimate does effectively buffer the panels against an environment in which the paintings are considered of lesser importance than the continued and unaltered use of the space.

Future work and direction

The NFC-sensor-tags are currently undergoing extended battery life testing to confirm the state model data presented in this paper. Tags have also been miniaturised since the pilot study was performed, with newer devices measuring 40 x 25 x 5 mm and weighing 7 g, including the battery. Motion and shock sensing NFC tags have since been developed and will be trialled and reported separately with art objects travelling on loan to guest institutions. In the longer term we expect to investigate and research alternative NFC protocols that allow higher data rates for faster file transfer. Latest generation ISO14443 tags for example now support data writes at 106 kbps and data reads at 424 and 848 kbps.

Conclusion

The results of this pilot study support the adoption and use of autonomous NFC-sensor-tags for cultural heritage and fine art *object-level* preventive care. The detailed performance analysis of the MCE in this pilot demonstrates how fine-tuning and monitoring of enclosure design can be undertaken. Importantly, *object-level* monitoring provides insight and visibility of the environmental conditions that fine art is exposed to on a daily basis. This information informs the conservator of exposure events that may indicate when or how observable damage has occurred. Longer-term, aggregated exposure data can be used by both conservators and institution management to tune exposure standards and to ensure compliance to those standards. This is possible on a case-by-case basis for individual works of art at the home institution and when out on loan. These new insights support conservators in their decision-making processes and aid institutional management in the formulation of long-term preventive care and loan strategies. With NFC devices available that cover the parameters of asset data, temperature, relative humidity, light level and motion, a major part of the monitoring needs of conservators, curators and museum administrators can be covered on this versatile and *unified* NFC technology platform.

Acknowledgements

The authors would like to thank the Master and fellows of Trinity College, Cambridge, for their support in hosting the pilot study, and Rupert Featherstone, Director of the Hamilton Kerr Institute, for supporting staff during this research. Simon Bobak and Ray Marchant of the Hamilton Kerr Institute's Ebury Street branch are gratefully acknowledged for the microclimate enclosure design used for the Trinity College panel.

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