Fidler, P. R. A., Vardanega, P. J., Hoult, N. A., & Middleton, C. R. (2021). Long-term monitoring of the Humber Bridge Hessle anchorage chamber. In H. Yokota, & D. M. Frangopol (Eds.), *Bridge Maintenance, Safety, Management, Life-Cycle Sustainability and Innovations - Proceedings of the 10th International Conference on Bridge Maintenaince, Safety and Management, IABMAS 2020: Proceedings of the Tenth International Conference on Bridge Maintenance, Safety and Management (IABMAS 2020), Sapporo, Japan, 11-15 April 2021* (pp. 1779-1786). (Bridge Maintenance, Safety, Management, Life-Cycle Sustainability and Innovations - Proceedings of the 10th International Conference on Bridge Maintenaince, Safety and Management, IABMAS 2020). CRC Press/Balkema, Taylor & Francis Group. https://doi.org/10.1201/9780429279119-242

Peer reviewed version

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10.1201/9780429279119-242

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Long-term monitoring of the Humber Bridge Hessle anchorage chamber

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ABSTRACT: Bridge engineers specifying, designing and installing Structural Health Monitoring (SHM) systems need to be able to provide reliable information over the very long design lives expected of critical infrastructure assets such as bridges. It is essential that asset managers can have confidence that any significant anomalies or changes in the performance of the structure will be detected. The resources and planning needed to keep such systems functioning is rarely reported as many research deployments are of short duration. In 2007 a wireless sensor network was installed in the Hessle Anchorage chambers of the Humber Bridge in the United Kingdom to monitor parameters that could affect the durability of the main suspension cables of the bridge. This deployment was part of a wider project aimed at examining the potential for using wireless network systems to monitor infrastructure assets. The initial planned duration of the project was six months. It has however now been in place and operational for over ten years. This paper discusses the maintenance undertaken, modifications required, and long-term performance of this installation along with the significance of the long-term data set that has been collected.

1 INTRODUCTION

1.1 *Background*

The Humber Bridge is an iconic structure which was opened in 1981 (Humber Bridge Board, 2020). In July 2017 the bridge was awarded Grade I listed building status by Historic England (Historic England, 2020). Many researchers have deployed structural health monitoring (SHM) systems on the bridge (e.g., Ashkenazi & Roberts, 1997, Stephen et al. 1993, Brownjohn et al. 1994, Brown et al. 1999).

In 2007 a Wireless Sensor Network (WSN) was installed in the Humber Bridge anchorage chambers in Hessle (on the north bank of the River Humber) by a team of researchers from the University of Cambridge as part of a wider Engineering and Physical Sciences Research Council (EPSRC) funded project studying the potential of wireless systems for use in structural health monitoring: 'Smart Infrastructure: Wireless sensor network system for condition assessment and monitoring of infrastructure'.

The monitoring system, which was initially only intended to run for six months, has been discussed in various papers. Hoult et al. (2008a,b) give details of the deployment and design of the system and follow-up reports on the data produced by the system have been published (Hoult et al. 2009a,b,c, Stajano et al. 2010). The deployment was also used as one of the calibration case-studies for the SHM value rating system presented in Vardanega et al. (2016a) and in the review of bridge monitoring systems presented in Vardanega et al. (2016b). While the deployment at Humber was only intended to trial commercial-off-the-shelf wireless sensor hardware in an infrastructure setting, the experience gained in deploying such a system was used to inform future deployments such as those at the Ferriby Road Bridge, located near the Humber Bridge (Hoult et al. 2009a, Hoult et al. 2010), the Jubilee Line Tunnel (Hoult et al. 2009b) and on the Hammersmith Flyover (Webb et al. 2014).

1.2 *Study Aims*

The monitoring system has now been deployed for over ten years and has been in near continuous operation during this period. The wireless sensor hardware used is largely unchanged from when it was originally installed in 2007. Most of the original Crossbow MicaZ motes and MTS400 sensor boards are still in use, although the batteries have been replaced multiple times, and with higher capacity batteries than those used in the original system. However, the wireless gateway has been relocated, and upgrades made to its original hardware. Two new temperature and humidity sensors were added as part of the gateway relocation. An inclinometer sensor added early in the deployment has subsequently been removed. The system has produced a long-term data set which is presented in this paper. This paper aims to report on the following: (1) The modifications made to the initial Humber anchorage deployment; (2) The efforts needed to maintain the monitoring system, e.g., number of battery changes, and (3) The humidity and temperature data collected during the deployment. Using the classification framework of Webb et al. (2015) this deployment is a ‘sensor deployment study’. It could also be classified as a ‘threshold check’ system as a relative humidity limit threshold of 60% for the anchorage area was assigned as discussed in Hoult et al. (2008a,b) based on the work of Nakamura & Suzumura (2005). However, no automated warnings were generated if this threshold was exceeded.

2 DEPLOYED SYSTEM

2.1 *Initial Deployment*

The configuration of the initial deployment has been reported in Hoult et al. (2008a, b). The basic layout is shown in Figure 1. The sensor system deployed in the Humber anchorage in 2007 consisted of the following key elements: (1) a Crossbow Stargate WSN gateway connected via an ADSL-enabled telephone line, (2) eleven Crossbow MicaZ wireless nodes with Crossbow MTS400 environmental sensor boards. In March 2008 a further Crossbow MicaZ connected to a bespoke inclinometer sensor board was added to the network. This was mounted on the saddle that supports the suspension cable as it enters the east anchorage chamber.

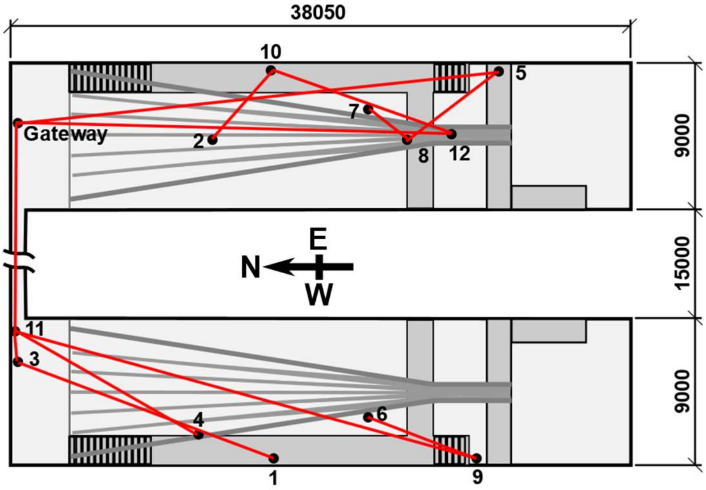

Figure 1. Plan view of the original deployment layout of wireless sensors (including inclinometer node 12 added in March 2008) overlaid with a typical network topology in East and West anchorage chambers (adapted from Hoult et al. 2008a) [adapted from Hoult et al. 2008. Turning the Humber Bridge into a smart structure. In: Koh & Frangopol (eds) *Bridge Maintenance, Safety, Management, Heath Monitoring and Informatics*, ISBN 978-0-415-46844-2, Taylor & Francis Group, page 1405, © 2008 Taylor & Francis Group, Reproduced with permission of the Informa UK Limited through PLSclear].

The gateway was originally deployed next to an ADSL-enabled telephone socket in the anchorage chamber. As the system was only intended to be deployed for six months, the gateway and modem were fixed to the wall using Velcro and duct tape to allow for easy removal without the need for permanent fixings (see Figure 2).

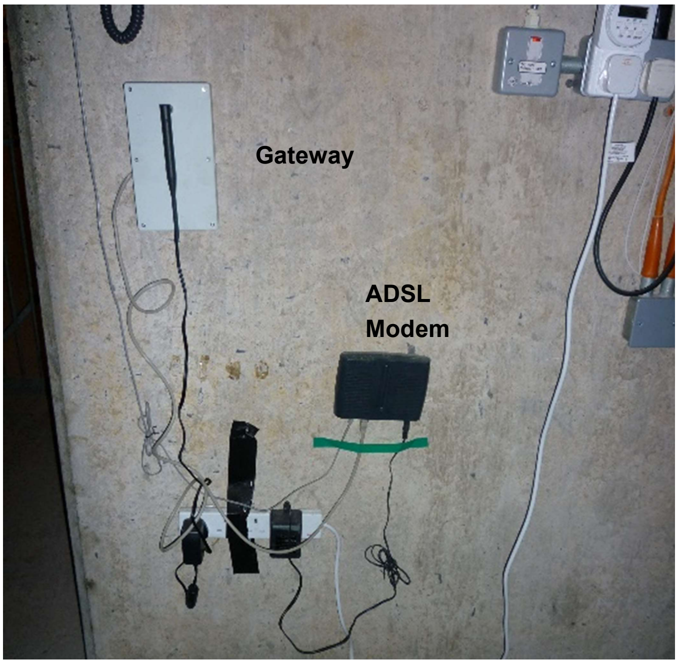

Figure 2. Original gateway and ADSL modem on the north wall of the east anchorage chamber Photo: Authors. (Photograph taken August 2009)

2.2 *Upgraded Deployment*

In July 2013 the ADSL connection was decommissioned, and the Humber Bridge Board instead provided a CAT5e Ethernet connection. This was located at a different position in the anchorage and therefore entailed relocating the gateway. It was decided that rather than move the original gateway (as no new updates or security fixes were available), a new gateway would be assembled and installed with long-term operation in mind (see Figure 4). One benefit of the original location of the gateway was its central position in the wireless mesh network topology (see Figure 1). The network was essentially in two halves, with the sensor nodes in each chamber relaying data to the gateway without using any nodes located in the other chamber.

As a result of the relocation of the gateway, the topology of the network would change with the new gateway location being topologically at one ‘end’ of the mesh network (see Figure 3). Nodes in the western chamber now depend on the nodes in the eastern chamber to relay data to the gateway. For this reason, two additional wireless sensor nodes (numbered 20 and 21) were added within the enclosure of the previous gateway in an attempt to ensure continued connectivity between the two halves of the network. Adding two new nodes was intended to provide a degree of redundancy. However, in practice node 21 relays its data through node 20 and never acts as a relay.

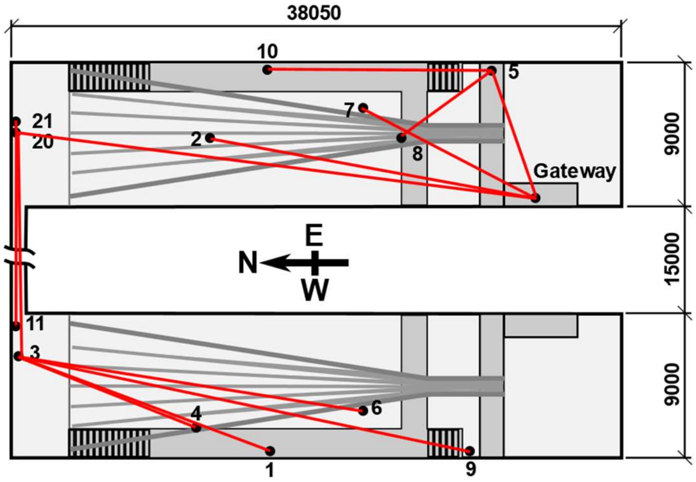

Figure 3. Plan view of the revised layout wireless sensors as at October 2017, overlaid with a typical network topology (adapted from Hoult et al. 2008a) [adapted from Hoult et al. 2008. Turning the Humber Bridge into a smart structure. In: Koh & Frangopol (eds) *Bridge Maintenance, Safety, Management, Heath Monitoring and Informatics*, ISBN 978-0-415-46844-2, Taylor & Francis Group, page 1405, © 2008 Taylor & Francis Group, Reproduced with permission of the Informa UK Limited through PLSclear].

Figure 4. New gateway installed in 2013. Photo: Authors. (Photograph taken November 2017)

In summary, the modifications to the initially deployed system were: (a) the repositioning of the wireless gateway to be close to the new Ethernet cable, (b) changing the wireless gateway from a Crossbow Stargate WSN gateway to a more robust system consisting of two Raspberry Pi single board computers, (c) the addition of two new wireless relative humidity and temperature sensors at the location of the old gateway, (d) the removal of the saddle inclinometer (as it was non-functional), (e) upgrading all wireless sensors in the system to use either D-cell or DD-cell lithium thionyl chloride batteries, and (f) the gateway software was re-written to send data to both the original database server as well as the one operated by representatives of the Humber Bridge Board.

The key benefit of using the Raspberry Pi was that it was low cost. Two were therefore purchased, offering some system redundancy for a lower cost than the original Crossbow Stargate board. Furthermore, the Raspberry Pi board was well supported with third-party add-on boards including the 'PiFace Digital' relay switch board. Each Raspberry Pi in the new gateway is fitted with a PiFace Digital board that allows each Raspberry Pi to power cycle the other. This has proved to be useful on occasions where it was suspected that one Pi had crashed. Without this reboot capability a visit to the anchorage chamber would have been required to power-cycle the system.

2.3 *System Maintenance*

The installation of a monitoring system on an infrastructure asset brings with it the requirement to maintain or replace the system to ensure acceptable performance and functionality. The monitoring system itself becomes an asset (or a liability) that needs to be managed. Although the system in the Humber Bridge Hessle anchorage was only intended to run for six months, the research team did endeavor to maintain the system for the full three years of the original research project, and then beyond as further funding became available. Table 1 gives details of the key events, including visits to the bridge since the initial deployment, indicating where battery changes and other modifications to the sensor system were implemented.

The initial months following installation were spent trying to solve connectivity issues between the sensor nodes: eventually solved by repositioning sensors either side of the passage that connects the east and west chambers and adding an additional relay node. Thereafter, fixes occurred on an ad-hoc basis as problems were identified. Battery changes were not systematic with batteries replaced in a few sensors at a time as they became depleted. To reduce the number of battery changes required the team attempted to increase the battery life first by doubling the number of AA batteries per node from two to four, using C-Cell lithium thionyl chloride batteries in some nodes, and finally upgrading all nodes to use either D-Cell or DD-Cell lithium thionyl chloride batteries. Node 12, the inclinometer, always used a DD-Cell battery. Between 2013 and 2017 battery changes were annual and involved changing the batteries in every sensor node. The batteries have not been changed since November 2017. This is to study the effective life of the system in the new configuration. At the time of writing, three of the sensor nodes remain functional. A further battery change is planned for 2020.

3 COLLECTED DATA

3.1 *Relative Humidity and Temperature data*

Figure 5 shows the changes in both humidity and temperature over the ten-plus years of monitoring. Outliers have been omitted from the temperature data. Seasonal temperature changes are clearly visible. There appears to be a slight year-on year increase in temperature, although this is mainly from 2016 onward. These corresponds with lower relative humidity in the two anchorages (now kept between 10% to 20% rather than 30% to 40% before 2016) meaning that the dehumidifiers, which tend to warm the anchorages, are active for longer periods.

In early 2010, a sudden increase in humidity – above the permitted the 60% threshold, were observed. This was due to the installation of a dehumidification system for the main suspension cables on the Humber Bridge, during which an entry hatch to the anchorage was left open for an extended period.

Two other sudden increases were observed on the 5th December and 16th January 2018, with relative humidity in the west anchorage peaking at over 80%. A further increase between 7th and 27th November 2018 when it appears that the dehumidifiers were switched off. This increase peaked at just under the 60% threshold needed to prevent corrosion to the cables. After communication with the Humber Bridge Board it was discovered that these periods coincided with works conducted between 2017 and 2018 to integrate the control systems for the anchorage and main cable dehumidification systems. There were periods when the anchorage dehumidification system was either off or running constantly (J. Barnes, personal communication, December 2, 2019).

3.2 *Wireless data transmissions*

Figure 6 shows a plot of the number of sensor data transmissions (excluding 'health' and statistics packets) received by the gateway per day. Since the gateway upgrade in July 2013 the amount of data received has been reasonably consistent at around 5,500 transmissions per day. Each sensor transmits data at approximately three-minute intervals and would therefore be expected to send around 480 data packets per day. With 13 working sensors, this would result in 6240 packets per day if all the data transmissions were successfully received at the gateway. Therefore 5500 packets per day represents is about 88% of would be achieved if the wireless system achieved perfect data delivery. The largest number of packets received on a single day is 6939 packets. This is actually more than the total number of packets sent by all the sensors. The inflated figure is accounted for by instances where the same packet is received at the gateway more than once – which can occur if reception was successful, but the acknowledgment packet was not received by the transmitting node.

There are periods when no data at all is recorded, shown on Figure 6 by the data packets received dropping to zero. These usually correspond with an intermittent fault with the gateway. One occasion in August 2008 it was as a result of a failed file system check resulting in the Stargate gateway mounting the These periods are usually brief but have been longer as there is no automated system to report the fault. These have been resolved remotely by manually logging into the second Raspberry Pi in order to reboot the primary Raspberry Pi.

The batteries in the wireless sensor nodes were last replaced in November 2017, and the graph shows a reduction in the quantity of transmissions received from November 2018 onward. This suggests that annual battery replacement is required for the system to remain fully operational.

4 SYSTEM PERFORMANCE

Using the vendor-supplied software, the sensor nodes take readings and send data to the wireless gateway at three-minute intervals. In principle, the nodes could sleep in a lower-power mode between readings and transmissions. However, the nature of the wireless mesh network used requires that all nodes must in fact wake up from sleep eight times per second to listen to transmissions from other nodes and, if necessary, relay these transmissions to the gateway, or to another relay node. The vendor supplied software did not use techniques such as time synchronization to reduce the need for periodic wake-ups.

In addition to reading temperature and humidity data, the nodes also send data on their battery voltage and statistics on the number of packets transmitted and relayed. This data is sent every 20 minutes. Nodes also send data on which other nodes are within range every 20 minutes.

A single pair of AA alkaline batteries will typically power a sensor node for 6-7 months, though this varies depending on its position in the network topology and therefore the number of packets it is required to relay for other nodes. One consequence of the change to using lithium thionyl chloride batteries was that there was no gradual fall in battery voltage prior to battery exhaustion. With the alkaline AA batteries, the nodes continued to function with battery voltages down to approximately 2.2V. The lithium thionyl chloride batteries, although significantly higher capacity (18Ah for a D-Cell) have more of a 'cliff-edge' battery voltage profile and can maintain 3.6V until a week or two before battery exhaustion.

This cliff-edge profile, as well as providing little warning for the asset manager, also provides no useful battery voltage data that could potentially be used by the routing algorithms on the nodes themselves when performing path-cost calculations, which might otherwise have avoided routing data through nodes

Table 1. Timeline of key events

Date	Description	Comments
2007		
5th and 6th July	Initial system installation	The system functioned as designed while the installation team was in the anchorage chamber. However, once the team had left, transmissions from all but four of the sensor nodes ceased to be received at the gateway.
23rd July	Repositioning of some sensors	Sensor nodes were moved to try to avoid issues with fading – where the antenna of one node is positioned such that no other node can receive its transmissions.
9th August	Wireless signal strength measurements	There were still difficulties with transmitting data through the tunnel between the east and west chambers. This visit was intended to resolve wireless propagation issues (see Hoult et al 2009c).
23rd August	Additional node added. Some sensors repositioned	Added new node 11 (without a sensor board) as a relay, and slightly repositioned some of the other sensors to improve the poor connectivity within the networks. Following this visit, data from all nodes are received at the gateway.
14th November	Modified code on the gateway	Data was being logged on the wireless gateway with implausible timestamps. Code was added to re-synchronize the clock on the gateway more frequently. This did not however cure the issue with incorrect timestamps.
2008		
19th March	Inclinometer sensor installed	Bespoke inclinometer node (number 12) installed on cable saddle. In addition to an inclinometer, it also has two relative humidity and temperature sensors.
10th April	Modified data logging code on the gateway	The issue with implausible timestamps was traced to using the Postgres database software on a relatively slow Crossbow Stargate gateway. The data logging code was therefore simplified to log to plain-text log files instead.
29th May	Partial battery change	Changed batteries in sensors 3 and 10.
24th June	Partial battery change	Changed batteries in sensors 1, 8 and 11.
15th August	File system fix	The gateway stopped functioning for several days. The cause was an issue with the ext2 filesystem on the CompactFlash card on the Stargate. Fixed remotely.
11th December	Partial battery change	Changed batteries in sensors 3 and 11.
2009		
22nd April	Battery change	Sensor nodes 3,5 and 10 upgraded to use C-Cell Lithium Thionyl Chloride batteries. Batteries changed in sensors 1,2,4,5,6 and 11.
31st July	End of funding from WINES Smart Infrastructure project	Interim funding secured from Humber Bridge Board to continue to maintain the system.
2010		
26th January	Battery change and upgrade	Sensors upgraded to double battery capacity by adding additional two additional AA batteries in parallel. Sensors 3, 5 and 10 not changed.
25th March	Battery change. Antenna upgrade.	Changed lithium thionyl chloride batteries in sensor nodes 3, 5 and 10. Upgraded sensor 5 antenna from 2 dBm to 5 dBm.
22nd November	Battery change and upgrade. Sensor software upgrade.	All nodes upgraded to use D-cell lithium thionyl chloride batteries. Sensor 11 was replaced due to damage All nodes reprogrammed with later version of the sensor board code from Crossbow - modified to reboot from time to time.
2011		
27th July	Battery change and upgrade	No issues. Node 11 replaced again – upgraded to DD-Cell battery. Also added a sensor board so node 11 is now a full sensor, not just a relay node.
2012		
12th January	Additional funding secured	Additional funding secured from Cambridge Centre for Smart Infrastructure and Construction to continue to maintain the system.
2013		
26th June	Battery change and gateway upgrade	Gateway was replaced by two Raspberry Pi single board computers and moved to a new location. Two new sensor nodes (20, 21) were added in previous location of gateway to act as relays. Batteries were replaced in all but 2 nodes (9 and 11 were inadvertently missed).
8th July	Battery change and upgrade	Sensor node 9 battery replaced. Nodes 3 upgraded with a DD-Cell lithium thionyl chloride battery.
2014		
23rd July	Battery change and upgrade	Node 12 (inclinometer) retired. Node 20 upgraded to DD-Cell lithium thionyl chloride battery.
2015		
10th August	Battery change	No issues.
2016		
25th October	Battery change	No issues.
2017		
8th November	Battery change	No issues.

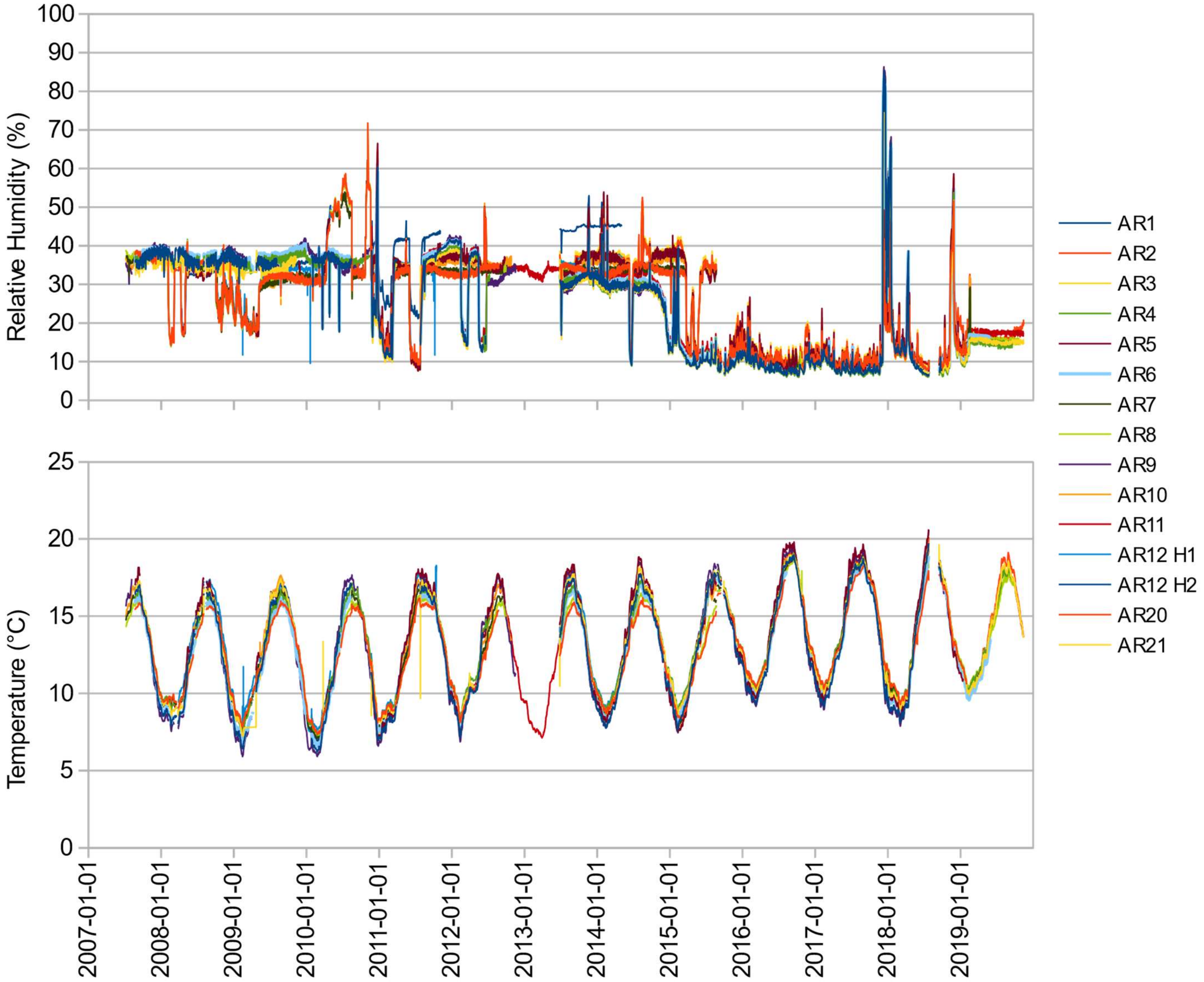

Figure 5. Ten years of Relative Humidity and Temperature Data from the Sensor System

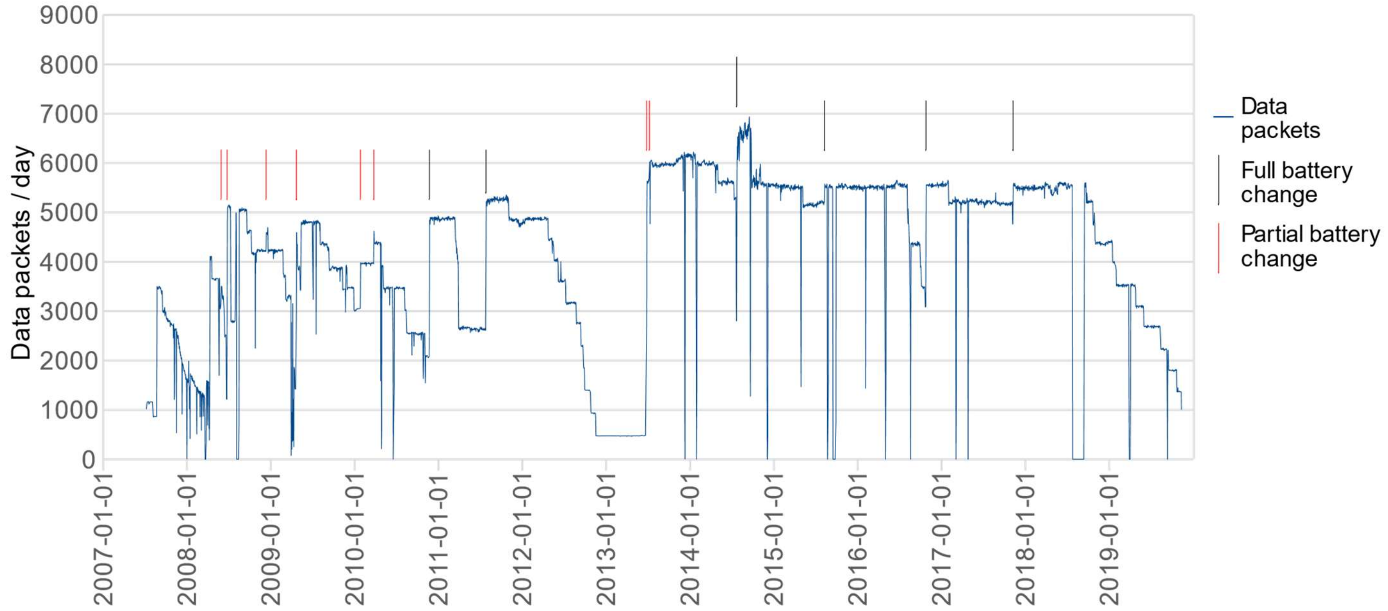

Figure 6. Plot showing the number of data transmissions per day received at the gateway

nearing battery exhaustion. The DD-Cell lithium thionyl chloride batteries perform well – sensor node 11 was able to function from July 2011 to June 2013 during which all the other nodes (at that time each using single D-Cell lithium thionyl chloride batteries) ran down.

The relocation of the gateway, although altering the topology, did not in fact adversely impact the performance of the network. Table 2 shows that in each configuration, all nodes were able to transmit data to the gateway with at most three hops. The average number of hops required per sensor node is slightly reduced in the new configuration. This may be due to the position of the new gateway. Although now at the south end of the eastern chamber, it is mounted higher than the original gateway. Sensor nodes 2 and 7 are now able to transmit to it directly.

5 SUMMARY

The monitoring system deployed on the Humber Bridge Hessle Anchorage has been in service for much longer than originally intended. The following summary points are made: (a) battery changes at intervals of approximately 1 year seem to be adequate to keep the system functioning, (b) the system proved flexible enough so that modifications could be made in-service without adversely affecting the operation of the system, and (c) the location for placement of the antenna and sensors is important (as described in previous studies).

Table 2. Number of transmissions (direct or via a relay) required to send data to the gateway

Sensor No.	Hops to Gateway in original configuration	Hops to Gateway in new configuration	Difference
1	3	3	
2	3	1	-2
3	2	2	
4	2	3	+1
5	1	1	
6	3	3	
7	3	1	-2
8	2	2	
9	2	3	+1
10	2	2	
11	1	2	+1
12	1	n/a	-
20	n/a	1	-
21	n/a	2	-
Average	2.0833	2	

DATA AVAILABILITY STATEMENT

The data supporting this publication is available from the University of Cambridge repository:
https://doi.org/10.17863/CAM.47827

ACKNOWLEDGEMENTS

This work was supported by the Engineering & Physical Sciences Research Council (EPSRC) grant no. **EP/I019308/1** Innovation Knowledge Centre for Smart Infrastructure and Construction and EPSRC grant no. **EP/D076871/1** Smart Infrastructure: Wireless sensor network system for condition assessment and monitoring of infrastructure. The authors also thank the many people who have assisted with various aspects of the deployment, in particular Peter Bennett, Ian Wassell, Yan Wu, Min Lin, Martin Touhey, Peter Hill, Andrew Scullion, Chris Day, John Williams, Ian Allenby, John Cooper, James Barnes, Kevin Moore and the Humber Bridge Board.

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