Tales from the Wild: Lessons Learned from Creating a Living Lab

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ABSTRACT

Wireless sensor networks in the past decade have become prevalent in areas such as environmental monitoring, hazard detection, and industrial IoT applications. Current research focuses on improving the energy efficiency, throughput, robustness, and resilience of such networks. Within this work, failures are rarely held up as something to be explored and discussed, as improvements and novelty are the traditionally highlighted outcomes. However, in order to undertake effective research, highlighting failures can help mitigate against them occurring in the future. In this paper, we wish to highlight failures in our work, times when engineering and social challenges were barriers to the completion of world class research. Three stakeholder driven case studies from the London Living Lab are chosen namely air quality, microclimate and urban bat monitoring. From these deployments, challenges are highlighted and the subsequent methods developed to overcome said challenges are explored with the view that future work may benefit from the outcomes of these experiences.

CCS CONCEPTS

• **Computer systems organization → Embedded systems**; *Redundancy*; • **Networks** → Network reliability;

KEYWORDS

Robustness,Resilience, In the Wild, Living Lab, IoT, WSN, Sensing Systems

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1 INTRODUCTION

Over the past decade sensing systems have matured to the point of widespread adoption. Sensor networks composed of low-cost, wireless, battery-powered devices are currently in use at scale in homes [1], industrial environments [2] and even entire cities [3]. In this context, a number of challenges have been encountered when enabling sustainable, robust Wireless Sensor Networks (WSN). Research to tackle these challenges have received a great deal of attention in both research and industry [4].

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In parallel, in many technology and engineering research disciplines, researchers are increasingly following "research in the wild" approaches to design, develop and evaluate prototypes [5]. This move to "in the wild" research methods is mainly driven by the acknowledgment that theories derived from lab studies often do not map onto the ways in which technologies must operate in the real world. For example, in the Human Computer Interaction community, researchers increasingly acknowledge that the real world is a series of emergent environments, characterized by a flow of changing variables that would be hard - if not impossible to recreate in a lab [6]. As such, researchers have looked to incorporate a greater level of ecological validity into studies and proof of concepts by testing prototypes in situ outside the lab, immersed in the real world environments for where they are intended [7, 8]. The result has been new insights and learnings into the practical and social impacts of prototype technologies that would not have emerged through lab trials alone [7, 9].

Over the past decade the research concept of "living labs" has emerged from ambient intelligence and user experience communities and formally established itself. A living lab is a space (often geographically bounded such as a city, neighborhood, park, etc.) where research and innovation happen in a public-private-people partnership [10]. It could be seen as a real world testbed where research in the wild is conducted, but where people are not merely observable entities but can also be part of the research and innovation processes in collaboration with researchers and key stakeholders. WSN research has begun to follow the common trend of in the wild design with many living labs now existing across Europe as part of the European Living Lab network [11] and beyond. City-wide living labs include Smart Santander [12], Porto Living Lab [13], and the London Living Lab in the UK [14].

A natural consequence of these developments is to start to explore failure in the context of WSN deployments. The papers [4, 15] present the experiences deploying a large-scale sensor network for residential and precision agriculture purposes. Interestingly, both papers highlight that the deployment was concluded without answering the initial research questions, however, they revealed many engineering problems typically overlooked when evaluating via simulation. However, as an outcome of this work lessons for the WSN research community as a whole are highlighted with risk mitigation strategies being put forth to reduce the chances of failure for future deployments.

The novelty of this paper lays in the incorporation of common experiences from disparate case studies in a Living Lab environment. Through said case studies, this paper highlights lessons learned from experiences undertaking long term in the wild experimentation.

(a) Example air quality sensor with components **(b) Example installation**

Figure 1: Example of an air quality sensor with an in-situ installation collocated with a ground truth air quality unit

2 CASE STUDIES

The work presented in this paper all constitute individual facets of the overarching London Living Lab environment. The London Living Lab is a city scale environment that is instrumented to enable experiments to be carried out in situ. The environments include schools, parks and city neighborhoods, which are instrumented and informed through an ethnographic research process. The multilayered, people-centric approach helps to better understand and design for a range of scenarios and use cases with communities, city officials and stakeholders to help design for the connectedness and sustainability of future cities. The current installation base is 150 gateways servicing 800 sensor end points.

Locations primarily revolve around the Queen Elizabeth Olympic Park (QEOP), which is the former site of the London 2012 Olympic Games, and since then has been undergoing a major legacy transformation as a new urban area with residential, commercial, cultural and leisure spaces as well as large areas of natural green space where plants and animal species can flourish. Park stakeholders want to better understand the health and biodiversity of this natural environment as well as how to best manage it and mitigate against negative impacts from surrounding building and development works.

Within this framework, three case studies are highlighted in this paper. In this section, we present the purpose, design, deployment, maintenance, and handover of these case studies, which consist of an air quality sensing system, an energy harvesting microclimate monitoring system for a wetlands environment, and an ultrasonic acoustic urban bat monitoring application.

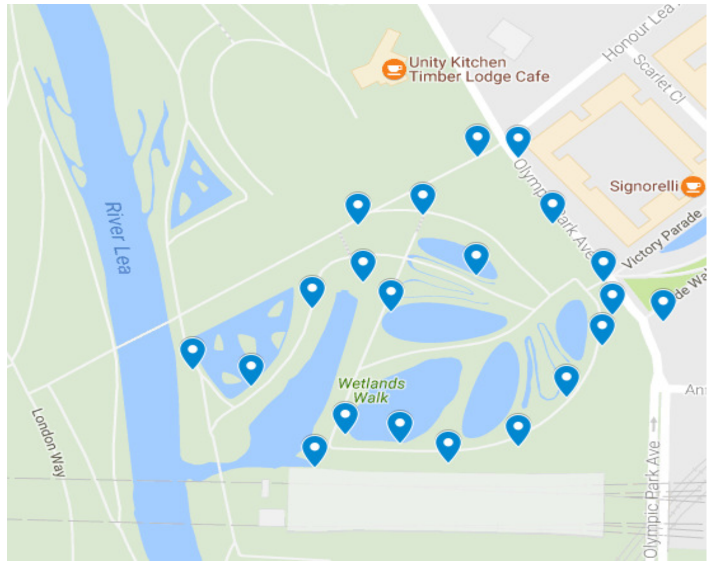
2.1 Air Quality

From a health perspective, the World Health Organisation has reported that over 7 million deaths around the world could be attributed to poor air quality in 2012 [16]. From a financial perspective, the costs of particulate matter (PM2.5) levels to the UK health system is 8 billion pounds per year, [17]. Within England, London has 86% of the worst areas for nitrogen dioxide (NO2) and 87% of the worst areas for dangerous airborne particles.

From exploratory meetings with government agents, schools, and community groups, air quality was constantly highlighted as a cause for concern. An IoT enabled air quality sensor was proposed to quantify air quality at a hyper-local level. From a domain perspective, existing work in air quality focuses on having a very accurate measure of air quality, resulting in a low number of sensing units, each with a very large cost. The research in this case study set out to answer the question "could a higher granularity of air quality sensing with lower cost devices potentially remove the need for the high-cost sensors entirely?"

The system designed, as can be seen in Figure 2b, was deployed in 120 locations across the London Living Lab. This system consisted of an Intel Galileo micro-controller, five air quality sensors measuring carbon monoxide, nitrogen dioxide, nitric oxide, sulfur dioxide and volatile organic compounds. In conjunction with the air quality sensors, temperature, humidity and light levels were included to give environmental conditions for post calibration purposes. Power was provided by mains power, data backhaul via a GSM network and enclosure designed to be IP-54 compliant. At the end of the experimentation phase, the ownership of air quality system was transferred to the various stakeholder groups involved in the project for the purpose of further experimentation.

(a) Example Micro-climate sensor.



(b) Deployment locations.

Figure 2: Sample Sensor and Locations of deployed sensor in Queen Elizabeth Olympic Park, London

2.2 Micro Climate Monitoring

QEOP contains ecologically diverse environments and is currently undergoing a rapid and sustained growth in terms of construction and land use. Stakeholders within the park were therefore concerned about the ecologically sensitive wetlands area of QEOP. From stakeholder workshops with the QEOP ecology team, it was determined that measuring of the microclimate of the wetlands area could provide insight into how this rapidly changing area was impacting local flora and fauna.

To this end it was determined that a self-powered, energy harvesting temperature, humidity, light and atmospheric sensors would be the most suitable solution for a microclimate monitoring application [18]. The system was designed to fulfill said requirements, Figure 2a shows one such sensor deployed in QEOP. The sensor system consisted of a Texas Instruments SensorTag which provides a micro-controller, a temperature, humidity, light, and atmospheric pressure sensor of sufficient data quality to serve the application needs determined. An energy harvesting solution consisting of an amorphous silicon solar cell and a nickel based rechargeable battery were chosen to act as an energy supply system. Data was backhauled via an RPL based mesh network to a mains powered IoT base station. The enclosure was designed to have an IP-65 level of waterproofing while still having a transparent cover to allow incident solar energy to hit the solar cell and light sensor and ventilation holes with a mesh cover were applied to the base of each unit so temperature and humidity could be accurately measured.

The sensors were deployed for two months to gather a baseline of data of how the wetland microclimate and equally understand the potential for energy harvesting in such an ecologically diverse area. The deployment was designed to be transient and has since been removed from the wetland area, with the potential for a future deployment if it is determined to be necessary.

2.3 Urban Bat Monitoring

Bats are an important species for environmental monitoring. They are often described as indicator species as their presence is a positive indicator of a healthy surrounding environment. As such, QEOP stakeholders invest in ongoing bat monitoring schemes across the park, contracting ecologists to carry out surveys over a few nights, several times per year. Ecologists use handheld ultrasonic recording devices and walk transects across the park over the course of several nights, capturing all audio. The audio (which can often be gigabytes or even terabytes of data) is then analyzed back in the lab to identify the abundance of bats and their species. This is a very time and labor intensive process (and therefore also costly) and only provides a small snapshot into bat activity levels over the few nights that recordings were taken.

The Nature-Smart Cities project was conceived to explore how Internet of Things technologies coupled with Machine Learning techniques could support bat monitoring across the park in a more continual and granular way. Technologists and ecologists designed and developed 15 smart bat monitors called Echo Boxes (see Figure 1). Each Echo Box captures full spectrum audio up to 96kHz (way above the human limit of 20kHz) and immediately processes the audio to identify if bats are present and what species they are. This processing happens in a matter of seconds on board the sensor device itself and then small results packets are sent across the network to cloud storage. By processing the audio on the sensor device at the edge of the network it is not necessary to transfer or store large audio files to the cloud, reducing network traffic and storage demands.

A network of fifteen Echo Boxes was installed across different habitats in QEOP in May 2017. To date, the network is detecting an average of 5000 bat calls per night and has classified up to five different bat species. The data can be viewed online at batslondon.com,

Figure 3: Echo Box enclosure

Figure 4: Internal view of the acoustic bat detector

including live updates during the night as bats are detected and classified in real-time. This is an unprecedented level of data for ecology monitoring and will provide an extremely detailed view of bat abundance and the health of the surrounding environments. The network of Echo Boxes will remain deployed in the park until the end of 2017, at which point the technology may be permanently transferred to park stakeholders.

Although each of these case studies served different needs for different stakeholders utilizing different technologies, common issues appeared consistently over the course of these deployments. In the next section, we discuss these challenges and present lessons learned to help mitigate against such failures for future research.

3 LESSONS LEARNED

From the deployments across the multiple case studies, challenges were encountered repeatedly which are highlighted in this section. From these common themes, solutions are proposed to minimize the risk to future deployments. Here we present five lessons learned from our work:

- Replicate in the wild setup for design and development
- Debug as you would in the wild
- Be aware of social challenges of research in public spaces
- Plan for leaving the wild
- Expect the unexpected

Replicate in the wild setup for design and development. When moving devices that have been designed and developed in the lab to their real world deployment locations, variations between the two environments can interfere with the operation of the system itself. For example, differences in the power supply, communication networks, and environmental inputs in the real world location can all cause system failure. Therefore it is advisable to replicate the wild setup as much as possible in the lab during the design and development of prototypes.

In the case of the air quality sensors, the variation in the power supply from the lab based wall sockets to waterproofed power supplies needed for long term deployments had a significant impact on the performance of the electrochemical sensors. Electromagnetic (EM) interference from the power supply in the field caused interference in the electrically sensitive electrochemical air quality sensors. In order to mitigate against this, the impact on EM shielding was explored, as can be seen in Figure 5. The electrically sensitive chemical sensors and their power supplies were electrically isolated from each other using EM blocking materials. Replicating the exact setup of the final deployment would have allowed this issue to be highlighted during in lab testing, saving time and money in the long term.

Dropouts in data processing can impact the performance of in the wild experiments. Replicating this in the lab to test the robustness of a network is crucial in debugging potential problems associated with a living lab deployment. For example, in the microclimate monitoring application, the base station lost power due to a faulty power supply. This caused the entire mesh network to repeatedly try to reconfigure until the base-station regained power. This caused the low power nodes to consume much more power during this time.They were not designed, or indeed expected, to be resilient to this type of failure.

In the case of the bat sensors, the biggest challenge was replicating system inputs in the lab, i.e. bat calls. Bats use ultrasonic frequencies (20kHz to 125kHz) for echolocation which lie beyond the range of human hearing. Replicating these ultrasonic calls is a major challenge as standard audio devices cannot make sounds at such high frequencies. Therefore, researchers had to design and custom build an artificial bat device using an ultrasonic Digital-Analog-Converter (DAC) and an ultrasonic speaker so that real-world bat calls could be replicated to some degree, as can be seen in Figure 6.

The additional work resulted in the detection of a new issue, as researchers in the lab were able to identify issues with the material used on the smart bat monitors to protect the ultrasonic microphone. The breathable fabric allowed air and sound waves to pass through (but not water particles); however, during testing with the artificial bat it was discovered that the material distorted the ultrasonic sound waves to the extent that the smart bat monitor was no longer

Figure 5: Air Quality Sensor EM shielding

able to detect bat calls - rendering it useless. After several redesigns, a solution was found to protect the microphone from water damage yet allow the ultrasonic soundwaves to pass through undistorted. Figure 7 shows the impact of this distortion against the original image.

The broad lesson learned across all of these experiments is that in order to maximise the chances of a successful deployment, it is advisable to replicate the wild setup in the lab from the outset, during the design and development of research prototypes. What may seem like valid assumptions about power supplies, communication networks or environmental inputs, can very easily lead to system failure at the point of real-world deployment.

Debug as you would in the wild. Related to the section above, when debugging prototypes in the lab during design and development, and performing recovery procedures after device failures, it is important to consider how such tasks would be performed in

Figure 6: Artificial bat ultrasonic device

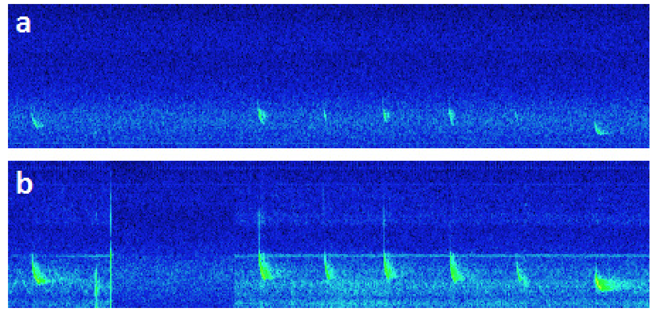


Figure 7: Original and distorted spectrogram

the wild if a similar bug or failure occurred. This is particularly important if the device is being deployed in less accessible locations.

The smart bat monitors in the Queen Elizabeth Olympic Park are installed on lamp posts at heights of greater than 4 meters, as can be seen in Figure 8. This is so that the public cannot tamper with the boxes, however, it also makes them completely inaccessible to researchers. Due to health and safety regulations (common across the UK), only approved engineers can ascend to the heights required to physically reach the boxes and must do so using cherry pickers or specialist ladder and harness systems, as in Figure 8, which can incur a large financial cost.

Therefore, once the boxes were installed on lamp posts it was undesirable for researchers to require physical access to them again. As one researcher commented "we might as well be sending them to the moon". As such, several measures were put in place so that the boxes could be accessed remotely and all maintenance and software updates performed without needing a physical connection to the boxes.

Additionally, when debugging the boxes in the lab before deployment, researchers tried to perform all necessary operations using only the tools and options that would be available to them when the boxes were deployed in the wild. As such, researchers refrained from plugging USB cables into serial ports to interact with devices or pushing hardware reset buttons, or power cycling the boxes - all options that would not be available to them once the boxes were deployed in the park.

Be aware of social challenges of research in public spaces. When conducting research in the wild, the experiment is often taking place in the public realm and hence methods, procedures and possibly also raw data are often on display in ways that they would not be in a lab environment. Additionally, devices and systems under test are in prototypical form, with iterations of improvements and optimisations still being carried out during the experiment lifetime. Therefore it is important to exercise appropriate controls over publicly visible aspects of in the wild deployments in order to manage expectations and retain credibility, yet still allow enough openness that ecological validity is not compromised, or that public anxieties or suspicions are not raised.

For example, the network of smart bat monitors in the QEOP was highly experimental with unknowns about how the hardware, software and machine learning algorithms would function once deployed. Researchers intended to monitor all aspects to better

Figure 8: Typical installation of a Living Lab sensor

understand and improve them during the course of the deployment, meaning that the system deployed at the start of the experiment was not yet optimal or validated. At the same time, park stakeholders were keen to promote the new bat sensing technology in the park and engage park visitors with the sensing devices and the data from them. As such, the boxes were designed to draw attention and clearly indicate their purpose (rather than being anonymous gray boxes), and a public visualization website was developed where anyone could view live bat data coming from the boxes.

Just prior to the public launch of the visualization website, researchers were faced with a dilemma. The hardware and software of the bat devices appeared to be working robustly, but the yet unvalidated machine learning algorithms were sometimes producing unexpected results such as bat calls being detected during the daytime, or rare species being detected that were highly unlikely to inhabit the park. Further investigation of the algorithms was required to validate the results being produced, but in the meantime, should the researchers share such unvalidated and questionable results publicly on the visualization website? Although disclaimers could have been attributed to the yet unvalidated results, researchers felt that it would not be enough to overcome potential damage to the credibility of the early system or their own credibility within research fields. As such, questionable results were filtered from

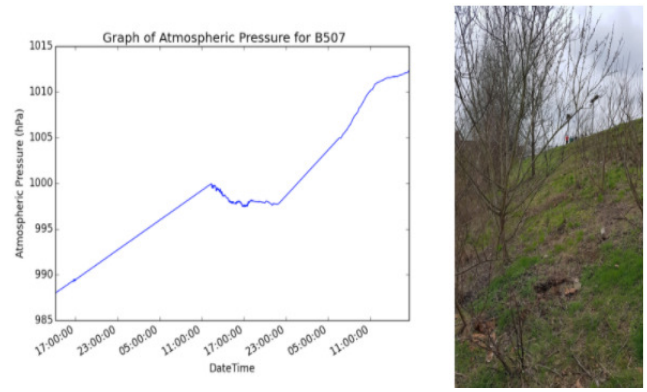


Figure 9: The impact of storm Doris in London, UK foreshadowing end of life of a sensor

the public visualization until validation and optimization activities could be completed.

Leaving the Wild. Across all of the case studies, planning around leaving the wild is as important as entering it. From the outset, it is advisable to plan with user stakeholders the long-term purpose of the living lab and the research being undertaken on it. In all experiments, there will come a time when the intended research has been undertaken from a research perspective. However, from a stakeholder perspective, services may have been built on the services and users become reliant on the infrastructure put in place in the living lab.

Often, at the end of the project stakeholders may not have the technical expertise to continue the project and (due to the nature of the source of the research based architecture) the platform would not be robust enough to survive without human intervention. Therefore, in order to give a deployment the best chance of success going forward, a transfer plan (which could include hiring in and transferring skills) is key in ensuring a successful continuing Living Lab in the wild.

Expect the Unexpected. Finally, despite designing for failure, undertaking laboratory testing to promote robustness, having a plan for engaging with the user stakeholders and a strategy for ending the experimentation, there are factors beyond the control of the experimenter that are encountered in the wild which can result in failures in experimentation.

Figure 9 shows the results of the data captured by the atmospheric pressure sensor in the microclimate monitoring case study. During the experiment, an unexpected failure of a sensor occurred, upon undertaking a site inspection it was discovered that the physical sensor was physically missing along with the tree that contained it. This failure was the result of a storm which swept the UK during the time of the experiment. Storm Doris had uprooted a number of trees in the wetlands, which were subsequently removed from the QEOP. The sensed data tells a story of its final hours. The sudden and rapid change in atmospheric pressure is a typical response to the oncoming storm and foreshadowed the eventual incident.

Another unexpected consequence of in the wild deployments was seen in Hyde Park, London as part of the air quality case study.

Figure 10: Air quality sensor after squirrel attack

If sensing systems are being placed in natural spaces, it was learned that the local wildlife will be naturally curious about this new object. As can be seen in Figure 10, one of the air quality boxes was eaten by a squirrel to the extent that it broke it's waterproof seal. This caused a premature failure of the system as the microcontroller board shorted due to water ingress and resulted in researchers having to replace the entire sensor to continue the air quality study.

In the Olympic Park, the smart bat monitors were positioned in varied contexts with different anthropogenic sounds created by many sources such as transportation infrastructure, events, and people going about their daily lives. Some sound sources, which had not been previously considered or tested in the lab, were able to confuse the bat sensors into thinking they were bat calls. One example was the clicking on bicycle gears that occurs while free-wheeling. This sound source produced ultrasonic frequencies with a very similar pattern to bat calls, often triggering the boxes to detect it as a bat.

Although the true heterogeneity of real world environments can not be fully predicted, one method to minimise the impact of the unexpected is via planning and over specification. Making room in the project budget for an extra site visit, create supplementary sensors to allow a fast changeover of a faulty device so the impact on the experiment is minimised. Another method is to create supervisory systems to monitor the infrastructure in situ and flag unusual behavior, such as a lack of reporting of data for an extended period. This will allow researchers to intervene and repair malfunctions as soon as is possible, rather than when a stakeholder interacts with the system and notices that it is no longer working.

4 CONCLUSION

In the world of WSN, in the wild design methods have allowed Living Lab environments to accelerate the pace of research by providing a method to rapidly deploy and test new ideas. However, the challenges in creating such a living lab should not be overlooked. In this paper, we explored multiple case studies undertaken in the London Living Lab, namely air quality, microclimate and urban bat monitoring.The purpose of this paper is to describe the failures, challenges and, subsequently, the lessons learned from these case studies. The lessons learned across the disparate case studies in the living lab, from providing adequate time to plan, debugging as you would in the wild, and protecting sensor systems from squirrel attacks will allow future researchers to avoid similar mistakes in the future and increase the likelihood of future in the wild research. As the famous George Santayana quote reminds us:

"Those who cannot learn from history are doomed to repeat it."

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