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Transforming bridges into smart infrastructure: a data-driven approach to monitoring bats and promoting sustainable coexistence

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Abstract

Introduction. Smart infrastructure development often prioritizes human needs such as safety and efficiency, overlooking the potential to facilitate coexistence with wildlife. This paper addresses this gap by demonstrating innovative use of internet of things (IoT) technology and data visualization for ecological monitoring.

Method. We repurposed commercially available wildlife trail cameras to collect data on bats roosting in bridges, despite commercial devices not being built for this application. Furthermore, we developed a map- and cloud-based dashboard to integrate this ecological data with existing bridge metadata, transforming raw sensor data into actionable insights for transportation authorities.

Analysis. We explore the ability of the dashboard to meet decision-making needs and offer design implications to further advance wildlife-inclusive smart infrastructure efforts.

Results. Our findings demonstrate the efficacy of using IoT devices for wildlife monitoring and the power of data visualization in informing conservation efforts within smart infrastructure development.

Conclusion. This study showcases the potential of IoT-enabled cameras and a user-friendly dashboard, BatMap, for effective bat monitoring and informed decision-making in infrastructure projects.

Introduction

Smart infrastructure, with its ability to collect and analyze real-time data on various aspects of urban environments, has significantly enhanced the decision-making capabilities of city officials and researchers (Hoult et al., 2009; Rejeb et al., 2022). This interconnectedness, combined with AI, enables the optimization of energy efficiency, informed city development planning, and improved navigation and overall human experience. However, the current focus of smart infrastructure and smart cities is often predominantly human-centric, overlooking the potential to benefit wildlife and promote sustainability (Azevedo Guedes et al., 2018; Mayrand & Clergeau, 2018).

Cities, while built with the intention of supporting humans, also serve as habitats for a variety of plant and wildlife species, contributing to both human well-being and the preservation of natural heritage (Forman, 2014). This realization aligns with the 'more-than-human' perspective in human-computer interaction (HCI), which challenges the traditional anthropocentric design focus and advocates for acknowledging the interconnectedness of humans, technology, and the natural world (Vallgårda & Redström, 2017). Embracing this perspective necessitates understanding how non-human inhabitants interact with and utilize urban spaces.

Such understanding is crucial not only for fostering coexistence but also for avoiding conflicts and seizing opportunities for conservation. For instance, critical infrastructure like bridges often serve as roosting sites for bats (Bektas et al., 2018). This can complicate maintenance projects due to the protected status of many bat species. However, recognizing their presence also highlights the potential for a more-than-human community within our cities (Bektas et al., 2018; Neuman, 2020). Current methods for monitoring bat presence, primarily visually inspecting bridges for bats, have limitations in terms of efficacy (Civjan et al., 2017; Adam & Hayes, 2000; Hendricks et al., 2005).

The challenges facing cities today, including climate change, necessitate innovative solutions and proactive governance. However, the lack of reliable, longitudinal data on urban wildlife populations hinders evidence-based long-term planning. To address this gap, we developed a passive monitoring approach using commercially available trail cameras to transform bridges into smart infrastructure, providing continuous and non-intrusive monitoring and video coverage of wildlife. The collected data is centralized in a cloud-based system, featuring a dashboard interface we call BatMap, which enables visualization, filtering, and facilitates user management.

This paper delves into the necessity for a decision-making tool like ours, employing a case study to illuminate our design process and the reasoning behind its specific features. The resulting design implications reveal how this system can enhance decision-making by furnishing reliable data on bat species, their activity patterns, and suggesting optimal timing for infrastructure maintenance to minimize the impact on wildlife.

The study underscores the potential of IoT-enabled cameras for wildlife monitoring, although it acknowledges the need for further optimization to boost detection rates. It further highlights the effectiveness of BatMap's interface and features in bolstering decision-making processes, particularly through its spatial and attribute-based information presentation. Moreover, the study emphasizes the importance of a 'more-than-human' design perspective in creating technology that benefits both humans and the environment. Finally, the potential of longitudinal data collection to inform conservation efforts and guide the development of wildlife-friendly infrastructure is also brought to light. The research aligns with the iSchools' Climate Action Coalition's focus on promoting interdisciplinary research for climate resilience and sustainable coexistence (iSchools, n.d.).

Specifically, we investigate:

RQ1: to what extent can IoT-enabled cameras and a cloud-based dashboard system effectively detect and monitor bat activity in bridges?

RQ2: how can the map-based dashboard interface support decision-making processes related to infrastructure maintenance and wildlife conservation?

Background

Smart infrastructure: a data-driven foundation for cities

Smart infrastructure, defined as technology capable of sensing its environment and taking automated action based on collected data (Ogie et al., 2017), has become integral to modern urban development. This distinguishes it from intelligent infrastructure, which generates insights requiring human intervention for action (Ogie et al., 2017; Jang et al., 2019; Chun & Ryu, 2019). The confluence of smart and intelligent infrastructure, coupled with the Internet of Things (IoT), allows cities and their infrastructure to become more efficient and responsive to users' needs (Rejeb et al., 2022).

Through a network of sensors deployed across various environments, smart infrastructure systems gather and analyze data to optimize functions like energy efficiency, infrastructure maintenance planning, and even traffic flow management. Technologies like RFID, wireless sensors, and data analytics facilitate real-time monitoring and control of resources such as lighting, public transit, and traffic patterns (Atzori, Iera, & Morabito, 2010; Wilson et al., 2015). Large-scale smart city and infrastructure projects have introduced diverse technologies, opening a plethora of innovative solutions for improved services (Hoult et al., 2009).

Among these technologies, wireless smart cameras are particularly prominent. Cameras equipped with AI and automation capabilities offer real-time monitoring and anomaly detection in sectors ranging from public transportation to building surveillance and wildlife management. For instance, Jang et al. (2019) employed cameras and line scanning with deep learning to detect anomalies in rail systems, showcasing the efficacy of camera based IoT systems for monitoring, protection, and timely insights. Similar advancements have been made in addressing challenges associated with monitoring surfaces exposed to weather conditions and constant motion, such as roads, to enhance image quality in suboptimal conditions (Chun & Ryu, 2019; Ai & Kwon, 2020).

Despite these advancements, current smart infrastructure initiatives often prioritize human needs, overlooking the potential to benefit wildlife and contribute to a more sustainable urban ecosystem (Azevedo Guedes et al., 2018; Mayrand & Clergeau, 2018). This anthropocentric bias limits the potential of smart cities to address broader ecological concerns and foster coexistence with non-human inhabitants. Our research aims to bridge this gap by leveraging smart infrastructure technologies for wildlife monitoring and conservation, contributing to a more holistic approach to urban infrastructure management.

Urban wildlife and the imperative of monitoring

While much of the current discourse on smart infrastructure centers on human-centric benefits like optimized energy consumption, improved transportation, and enhanced urban living (Neuman, 2020; Popescu, 2022), there is a growing recognition of the need to consider a "more-than-human" perspective. This perspective emphasizes the role of cities as habitats for diverse plant and wildlife species, acknowledging their contribution to human well-being and ecosystem health (Bektas et al., 2018; Maynard and Clergeau, 2018).

Research is increasingly revealing the potential for smart infrastructure to support biodiversity and contribute to sustainable ecosystems (Maynard and Clergeau, 2018; Neuman, 2020; Lashof and Neuberger, 2023). Green spaces, urban forests, and rooftop gardens, for instance, can serve as vital habitats for wildlife while also improving air quality and providing recreational areas for humans

(Neuman, 2020). However, city managers are sometimes focused on how to remove unwanted animals from city infrastructure, rather than promoting coexistence (Hadidian, 2015). Recent research has indicated that there are costs to decreasing biodiversity that are directly linked to human mortality (Frank, 2024). By designing cities and their technologies with all inhabitants in mind, we can foster biodiversity conservation alongside smart infrastructure deployment (Bektas et al., 2018).

Moreover, integrating green elements into infrastructure, such as green walls and roofs, can provide additional living spaces for wildlife and promote sustainable human-computer interaction (Maynard and Clergeau, 2018). This approach aligns with the broader goal of designing technology for sustainability, enabling smart cities to serve all inhabitants efficiently while reducing power consumption, traffic congestion, and pollution (Neuman, 2020; Hansson et al., 2021).

Beyond environmental sustainability, smart cities also have the potential to support both human and non-human interests. Popescu (2022) explores how the management of waste, water, and infrastructure systems can be optimized to reduce waste, improve recycling, and mitigate environmental and infrastructure degradation. These efforts, while often focused on human communities, can unintentionally benefit wildlife by preserving ecosystems and reducing the impact of extreme weather events. Lashof and Neuberger (2023) further highlight the need for adaptive infrastructure that prioritizes both human and environmental health by reducing emissions.

Effective wildlife monitoring is essential for understanding urban ecosystems and making informed decisions about infrastructure development and maintenance. However, traditional monitoring methods, such as visual surveys, often face limitations in terms of accuracy, efficiency, and the ability to collect long-term data (Civjan et al., 2017; Adam & Hayes, 2000; Hendricks et al., 2005). This is particularly true for species like bats, which often roost in less accessible areas like bridges and tunnels.

The challenges associated with wildlife monitoring underscore the need for innovative approaches that leverage technology to provide reliable, longitudinal data. Such data can empower decision-makers to anticipate conflicts, minimize environmental impact, and foster a more sustainable coexistence between humans and wildlife in our cities.

More-than-human perspective in HCI: designing for coexistence

The design and implementation of technology carry significant implications, particularly concerning their impact on the environment and non-human inhabitants. While smart buildings offer energy efficiency and enhanced functionality for human users (Atzori, Iera, & Morabito, 2010), the field of human-computer interaction (HCI) has traditionally been anthropocentric, often overlooking the needs of other species. This gap is particularly evident in research on small mammals like bats, which are underrepresented in HCI and animal-computer interaction (ACI) studies (Koche et al., 2021).

However, the aforementioned 'more-than-human' perspective is emerging within HCI, advocating for a shift away from human-centered design and towards acknowledging the interconnectedness of humans, technology, and the natural world (Vallgårda & Redström, 2017). This approach emphasizes recognizing and valuing the agency and the influence of non-human entities in the design and use of technology. It encourages us to consider how our technological creations impact the environment and other species, fostering a sense of shared responsibility and coexistence.

Furthermore, sustainable human-computer interaction (sHCI) emphasizes the importance of designing technology that is environmentally sustainable, socially responsible, and economically viable in the long term (Biggs et al., 2021; Dourish, 2010; Hansson et al., 2021). This includes considering the entire lifecycle of technology, from resource extraction to disposal, and ensuring its minimal impact on the environment.

The collection and analysis of real-time data on wildlife activity patterns, enabled by smart infrastructure technologies, can play a crucial role in promoting sustainable coexistence. By understanding how non-human inhabitants utilize urban spaces, we can make more informed decisions about urban planning and infrastructure development. For example, data on bat roosting locations can inform maintenance schedules for bridges, while minimizing disruptions to their habitat. This data-driven approach aligns with the ‘more-than-human’ perspective by acknowledging the agency of non-human entities and incorporating their needs into the decision-making process.

Ultimately, a shift towards a more-than-human approach in HCI and urban planning can help us create cities that are not only smart and efficient but also sustainable and inclusive for all inhabitants, both human and non-human.

To demonstrate the potential of a more-than-human approach in urban planning and wildlife conservation, we present a case study focused on monitoring bat populations in bridges using smart infrastructure technologies. In the following section, we outline the methodology employed in this study, detailing the data collection, analysis, and visualization techniques used to gain insights into bat activity patterns and inform decision-making.

Methods

Case study approach

This research employed a case study methodology, involving a collaboration between university researchers from the fields of biology and information technology, and the Ohio department of transportation. The primary goal was to develop and evaluate a system for monitoring bat activity in bridges, contributing to informed decision-making regarding infrastructure maintenance and wildlife conservation. The case study involved the deployment of IoT-enabled cameras on bridges to collect data on bat presence and activity patterns. This data was then integrated into a custom-designed, cloud-based dashboard, BatMap, to facilitate visualization and analysis.

Data collection: deploying trail cameras on bridges

To assess the feasibility of using trail cameras for bat detection, we tested several trail cameras for performance in this use case. We selected and strategically deployed Reolink Keen Ranger PT cameras under 27 bridges in Ohio, USA. The camera model was chosen for its rapid trigger speed, no-glow night vision, high video quality, and internet connectivity, features crucial for capturing clear videos of bats, particularly at night.

Deployment sites were selected based on cellular service availability for remote control and data retrieval, while avoiding bridges over high-traffic areas or large waterways. Cameras were mounted in potential bat roosting areas, such as expansion joints (Bektas et al., 2018), using double-sided tape (Figure 1). The Reolink mobile app facilitated precise camera aiming (Figure 2). All fieldwork was conducted with necessary permissions and in coordination with authorities.

Figure 1. A trail camera deployed underneath a bridge

Initial trials revealed improved bat detection and video quality with supplemental infrared (IR) lighting. Therefore, external battery-powered IR illuminators with timer-controlled power supply were deployed at each camera location. Cameras remained active for 1–23 days (average = 10.2 ± 5.5 SD), limited by factors like battery life, theft, or study completion. Captured videos were transmitted to the Reolink cloud service and subsequently downloaded to Microsoft OneDrive for storage and analysis. Two experienced bat ecologists reviewed all videos to confirm bat presence and identify species.

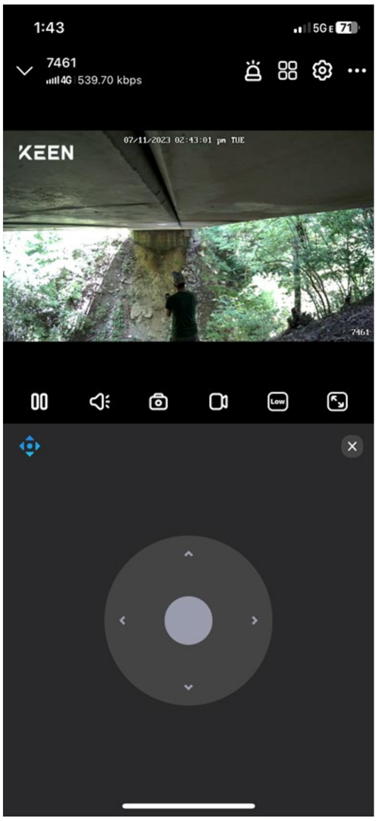

Figure 2. Screen capture from Reolink mobile app, showing researcher aiming a camera during deployment

Data analysis and visualization: BatMap dashboard

To effectively manage and visualize the collected data, we developed BatMap, a map-based dashboard tailored to the department of transportation's needs. It utilized HTML, CSS, and JavaScript for the front end and a MySQL database on a university web server for the back end, handling various requests.

BatMap's ability to display data across time allows for insights into long-term bat activity patterns, addressing limitations of traditional surveys and accounting for bat migration. It aims to facilitate informed decision-making regarding infrastructure projects and minimize disturbances to bat populations.

This case study approach, combining IoT-enabled cameras with a custom-designed dashboard, allows us to investigate the effectiveness of this system for bat monitoring (RQ1) and evaluate how the dashboard interface supports decision-making related to infrastructure and conservation (RQ2).

Results

Effectiveness of IoT-enabled cameras for bat detection and monitoring (RQ1)

Our deployment of IoT-enabled cameras across 27 bridges resulted in bat detection at 4 sites (15%), offering initial evidence for the potential of this technology in transforming bridges into smart infrastructure for wildlife monitoring. Over a 60-day deployment period at these occupied sites, bats were recorded on 8 nights (13%). The captured videos clearly showed bats entering and exiting the bridges, typically within a few seconds, demonstrating the system's ability to detect and record bat activity (Figure 3).

These findings suggest that while the overall detection rate across all deployed sites was relatively low, the system proved effective in identifying bat presence at bridges where they were actively roosting or utilizing the structures. The high-quality video capture, particularly at night, facilitated clear identification of bats despite their rapid movements.

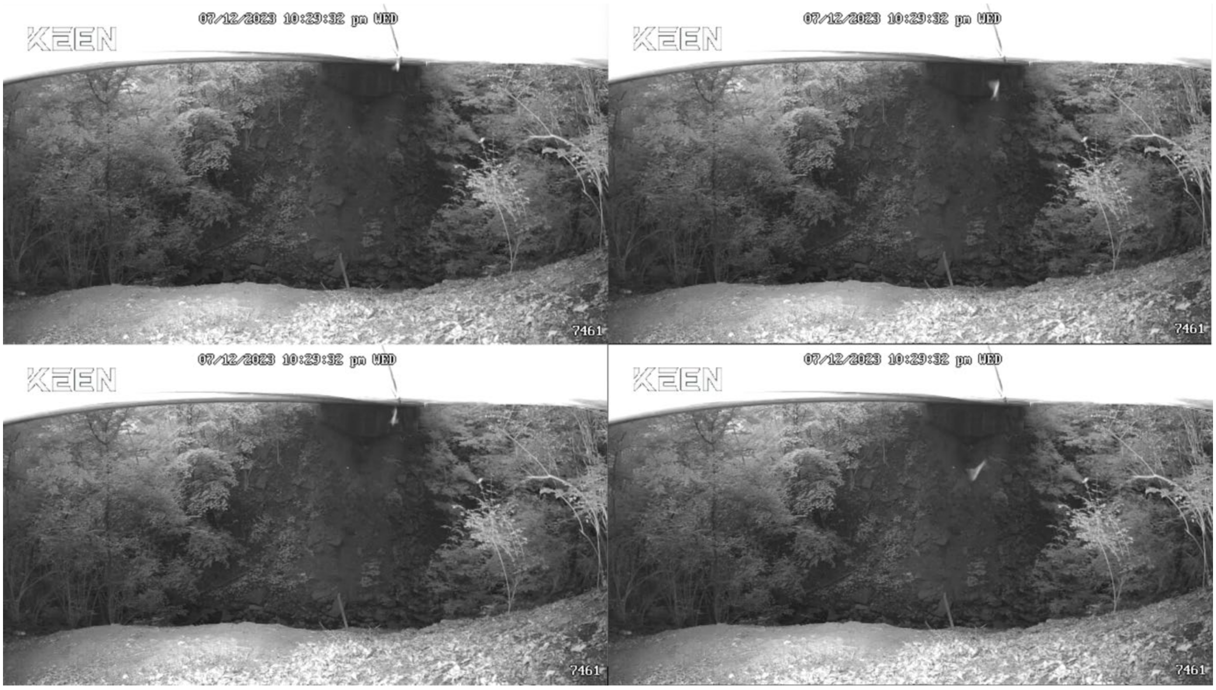

Figure 3. Bat capture evidence from our camera deployment

BatMap dashboard: supporting decision-making (RQ2)

BatMap's interface was designed to facilitate informed decision-making regarding infrastructure maintenance and wildlife conservation by providing readily accessible and relevant information to users. All features were discussed with collaborators at the state Department of Transportation during monthly meetings prior to implementation. The following describes features that were included in the design. This is followed by a description of how the system was designed to meet the decision-making needs of the Department of Transportation, and an example of how the dashboard has been used.

Split-screen layout: the map and search/local inventory side-by-side configuration allows users to simultaneously view spatial data on bridge locations, natural areas, and waterways, fostering a holistic understanding of the ecological context surrounding infrastructure (Figure 4).

Bridge List: this feature offers high-level information on bridges displayed on the map, including the Structure File Number (SFN), district, county, and any existing survey data (Figure 4). This enables project planners to quickly identify bridges requiring bat surveys or prioritize maintenance based on proximity to bat habitats or other critical natural resources.

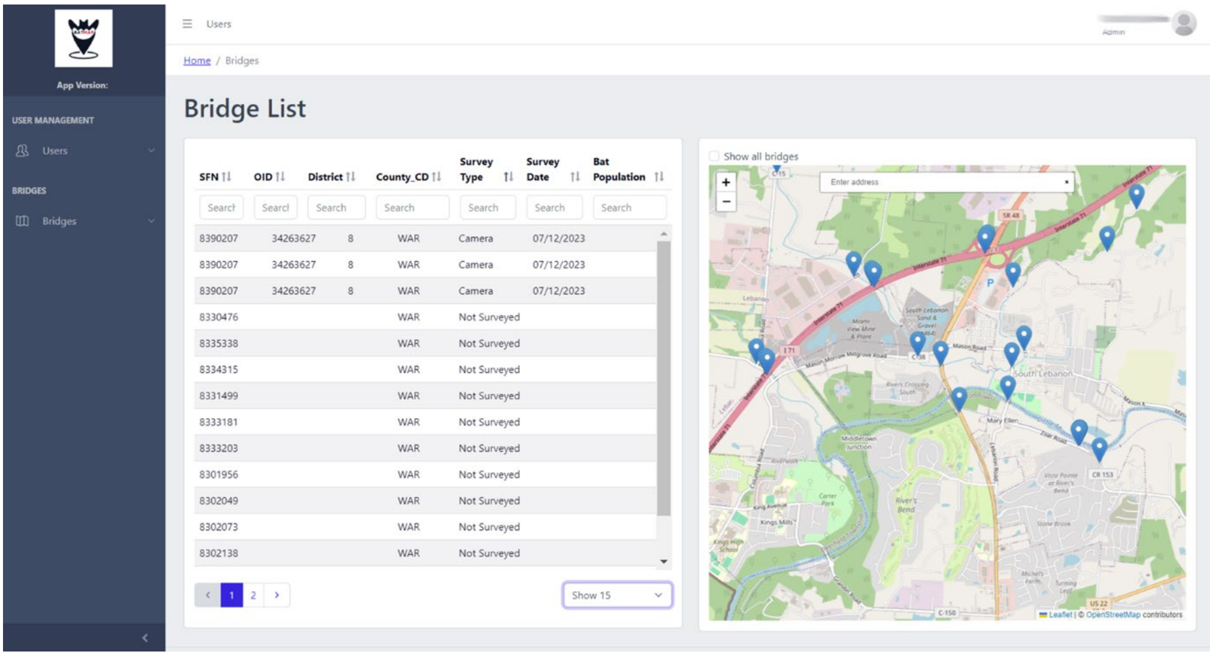

Figure 4. Screen capture of a user's split-screen view upon logging in to BatMap

Bridge Profile: clicking on a bridge in the bridge list or on the map opens a detailed profile displaying structural attributes and environmental factors known to influence bat use. This feature caters to both experienced bat ecologists and those less familiar with bats, thus aiding in informed decision-making (Figure 5). The inclusion of uploaded photos and videos provides visual evidence of bat presence, further aiding in assessment.

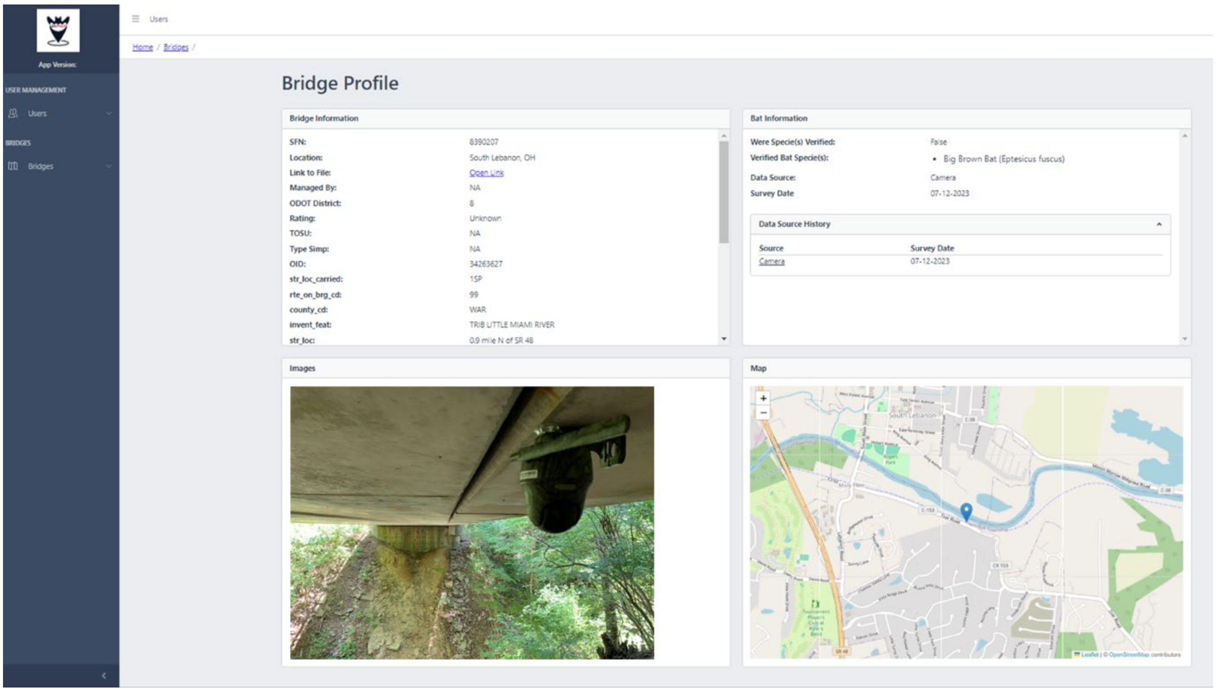

Figure 5. Screen capture of BatMap's Bridge Profile page

Map Integration: the persistent map within the Bridge Profile reinforces the spatial context, allowing users to visualize the bridge's location in relation to surrounding natural features.

By integrating these features, BatMap supports decision-making processes related to infrastructure maintenance and wildlife conservation in several ways:

Prioritization of Surveys: the system enables project planners to efficiently identify bridges in need of bat surveys, prioritizing those with no prior data, proximity to known bat habitats, or areas of ecological significance.

Informed Maintenance Planning: the Bridge Profile provides insights into the likelihood of bat presence based on structural and environmental attributes, enabling planners to schedule maintenance activities during periods of low bat activity or implement mitigation measures to minimize disturbance.

Data-Driven Conservation Efforts: the longitudinal data collected by the system can contribute to broader conservation efforts by identifying critical bat habitats and informing the design of wildlife-friendly infrastructure.

Knowledge Sharing and Awareness: BatMap's user-friendly interface and accessible information foster knowledge sharing and raise awareness about the importance of considering wildlife in infrastructure planning and management. The system was built with a level of security to ensure that the locations of sensitive species are not publicly available but are accessible to relevant managers who require such information for conservation and decision-making purposes.

In summary, BatMap's design is intended to empower decision-makers with the information and tools needed to balance infrastructure development with wildlife conservation while ensuring the safety of sensitive information, fostering a more sustainable coexistence between humans and the natural world in urban environments. In the same year that we made BatMap available to the Department of Transportation, the dashboard was used effectively to respond to a report of a colony of state-endangered bats roosting underneath a bridge that was scheduled for replacement in several years. Although the planning and contracting for the bridge replacement had already been completed, BatMap was still used to acquire situation awareness. Specifically, Department of Transportation planners were able to query the bridge from the Bridge List and see that no bat surveys had ever been conducted at the site. They also used the integrated map to quickly determine if surveys had been conducted at any nearby bridges to determine if additional conflicts between planning and conservation might exist. Finally, they were able to devise a plan for mitigating impacts on the bat colony by considering the ecological context of the bridge, including where supplemental habitat could be provided for the bats during construction.

Discussion

The results of this study offer several design implications for the development of smart infrastructure systems that support both human needs and wildlife conservation.

Effectiveness of IoT-enabled cameras

The successful detection of bats at 15% of deployed sites demonstrates the potential of IoT-enabled cameras as a tool for wildlife monitoring, aligns with research that emphasizes the importance of careful deployment strategies to maximize detection rates in wildlife monitoring using camera traps (Rovero & Zimmermann, 2016). However, the low overall detection rate suggests the need for further refinement and optimization of camera placement and settings. Future research could explore the use of machine learning algorithms to improve bat detection accuracy and reduce false positives (e.g., recordings of insects), echoing studies that have successfully applied AI-powered image analysis to identify and classify various wildlife species (Norouzzadeh et al., 2018).

BatMap dashboard for decision-making

The positive feedback from the Department of Transportation collaborators regarding BatMap's interface and features underscores its potential to support decision-making processes, highlighting the importance of user-centered design in developing effective decision-support tools (Kujala, 2003). The split-screen layout, bridge list, and bridge profile were thought to be particularly useful for prioritizing surveys, planning maintenance activities, and fostering awareness of bat presence. These design elements, particularly the combination of spatial and attribute-based information presentation, align with research on geospatial visualization, which emphasizes the value of integrating multiple data layers to facilitate understanding and decision-making (MacEachren & Kraak, 2001). By providing users with both spatial and attribute-based information in an easily accessible and understandable format, BatMap empowers decision-makers to make informed choices that balance infrastructure development with the needs of wildlife.

More-than-human design

The integration of wildlife monitoring capabilities into smart infrastructure reflects the growing interest in "more-than-human" design in HCI, which challenges anthropocentric perspectives and advocates for considering the needs of non-human entities (Vallgårda & Redström, 2017). This study demonstrates how such an approach can lead to developing systems that not only enhance human experiences but also contribute to environmental sustainability and wildlife conservation, aligning with the concept of sustainable HCI, which emphasizes the need for technology to support both social and ecological well-being (Blevis, 2007).

Data-driven conservation

The collection of longitudinal data on bat activity patterns has the potential to inform broader conservation efforts and contribute to the design of wildlife-friendly infrastructure. This aligns with research emphasizing the importance of long-term monitoring for understanding wildlife populations and their responses to environmental change (Magurran et al., 2010). Future research could explore the use of this data to model bat habitat preferences and predict potential conflicts with infrastructure development, echoing studies that employ species distribution modeling to inform conservation planning and mitigate human-wildlife conflicts (Guisan et al., 2013).

Limitations and future directions

While this study provides promising results, it is important to acknowledge certain limitations. The relatively small sample size of bridges in one mid-western US state and the focus on a single taxonomic group (bats) limits the generalizability of the findings. This resonates with calls for more inclusive and diverse perspectives in HCI research, including a broader consideration of non-human stakeholders (Bardzell, 2010). Further research is needed to explore the applicability of this approach to other wildlife species and infrastructure types.

Additionally, the study relied on commercially available trail cameras, which may have limitations in terms of sensitivity and image quality in certain conditions. One such limitation is the ability of the built-in IR lights, to illuminate small, fast-flying bats from distances >20 m. The development of specialized sensors or the integration of AI-powered image analysis could further enhance the system's capabilities. This aligns with research on the use of emerging technologies, such as drones and bioacoustics, in ecological research and conservation (Linchant et al., 2015; Aide et al., 2013).

Future research should also investigate the long-term impact of this system on decision-making processes and conservation outcomes. It would be valuable to assess whether the data provided by BatMap leads to tangible changes in infrastructure maintenance practices and contributes to the protection of bat populations. Overall, this study demonstrates the potential of integrating wildlife monitoring capabilities into smart infrastructure to support a more-than-human approach to urban planning and development. By leveraging technology and data-driven insights, we can create cities that are not only efficient and livable for humans but also sustainable and inclusive for all inhabitants.

Conclusion

This study demonstrates the potential of integrating IoT-enabled cameras and a custom-designed dashboard, BatMap, for effective bat monitoring and informed decision-making in the context of urban infrastructure maintenance. Our study successfully demonstrates the potential of IoT-enabled cameras for bat monitoring (RQ1). While bat activity was detected at a moderate 15% of surveyed bridges, the system's ability to capture clear video evidence, even in low-light conditions, underscores its promise for transforming bridges into valuable components of smart infrastructure for wildlife conservation. These findings suggest that with further refinements, such as optimizing camera placement and incorporating AI-powered detection algorithms, the effectiveness of this approach can be significantly enhanced.

Moreover, the positive reception of BatMap by Department of Transportation collaborators highlights the value of a user-friendly, map-based dashboard in supporting decision-making (RQ2). By integrating spatial data visualization, detailed bridge profiles, and multimedia evidence, BatMap empowers users to prioritize surveys, plan maintenance activities strategically, and foster awareness of bat presence. This demonstrates the system's potential to facilitate data-driven decision-making that balances infrastructure development with the needs of wildlife, contributing to a more sustainable coexistence in urban environments.

This research contributes to the fields of information and data science, particularly within the context of the iConference community. We showcase a novel application of IoT technology and data visualization in the realm of wildlife monitoring and conservation, underscoring the valuable potential of interdisciplinary collaboration between information technology and biology.

Furthermore, our work champions a more-than-human approach by integrating wildlife monitoring capabilities into smart infrastructure, thereby adding to the growing body of research that challenges anthropocentric design paradigms. This approach resonates with the iSchools' Climate Action Coalition's vision, promoting interdisciplinary efforts towards climate resilience and sustainable coexistence.

BatMap's user-centric design empowers decision-makers with accessible and pertinent information, enabling them to make informed choices that minimize the environmental impact of infrastructure development. This exemplifies the power of data science in bridging the gap between research and real-world application, fostering evidence-based decision-making that benefits both human and non-human communities.

In conclusion, our study highlights the feasibility and positive impact of employing IoT-enabled cameras and a tailored dashboard for bat monitoring and conservation within urban settings. These findings emphasize the necessity of adopting a more-than-human perspective in the design and implementation of smart infrastructure, ultimately envisioning cities that are not only technologically advanced but also ecologically balanced and sustainable.

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