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Automatic Embedded System for Surveillance of Birds Nesting in Boxes

Dissertation thesis

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Branch of study: Applied and Landscape Ecology
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Prague, August 2019

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Declaration

I hereby declare I have written this doctoral thesis independently and quoted all the sources of information used in accordance with methodological instructions on ethical principles for writing an academic thesis. Moreover, I state that this thesis has neither been submitted nor accepted for any other degree.

In Prague, August 2019

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Ing. Petr Kubizňák

Acknowledgements

Many people participated in this project. My first thanks go to the core members of our team – M. Zárybnická for project leadership, T. Kotek for server maintenance, P. Junek and J. Kuchař for webserver development, V. Osoba for enthusiastic work as a field technician, and J. Šindelář and R. Ševčík for field works. Second, I would like to thank the Elnico company, namely J. Kubizňák, my father, for great hardware design and support of the project, and R. Horák for patience in production. Third, thanks belong to other members of the team – V. Klapetek for designing the wooden box, J. Bartoška and J. Hruška for support on the server software, and many students for field works and data analyses. I thank W. M. Hochachka for great contribution to the third manuscript and V. Hlaváč for long-term project support and thesis review. I also thank countless applicants for their assistance and willingness to participate in our project. My honest gratitude belongs to all developers of free and open-source software without which this work would never come true. And finally, big thanks belong to my wife for her support and patience, and my little daughter for her smiles.

This project was funded by the Operational Programme Prague – Growth Pole of the Czech Republic (CZ.07.1.02/0.0/0.0/16_023/0000111), the Czech University of Life Sciences Prague (CIGA 20144203, 20164202, 20174203), the License Fund of the Czech University of Life Sciences Prague, Česká spořitelna a.s. (99200/1710/7133), and the Czech Technical University in Prague (TACR grant No. 01020197).

The developed surveillance system is protected by a Czech utility model No. 27722: "Smart nesting box for birds", registered in 2015, owned by Czech University of Life Sciences Prague, Czech Technical University in Prague, and Elnico s.r.o.

Abstract

This dissertation thesis summarizes the development of an autonomous electronic system designated for monitoring of animals in artificial nest boxes. This system, functioning as a camera trap embedded in a wooden box, is capable of recording high-definition videos of activities inside the nest, enriched by a range of ancillary data. Three models of the system were gradually developed. Model 1.0 was a battery-powered, offline-operated system designed for research on Tengmalm's owl (*Aegolius funereus*) in the natural environment. Model 2.0, targeting on songbirds monitoring in an urban environment, was designed as an Internet of Things device with permanent connectivity to our server and powering from mains. Model 3.0 was designed as a superior solution intended for both use cases. Our proof-of-concept showed enormous potential in the combination of Citizen Science and the Internet of Things for autonomous collection of an unprecedented amount of biological data for research purposes and public education. Evaluation of such amount of data is challenging and remains open for future research and development. The thesis relates to the articles published in impacted journals: Methods in Ecology and Evolution (IF 5.708), Folia Zoologica (0.592) and Ecosphere (2.746).

Keywords: Smart nest box, Camera trap, Surveillance system, Internet of Things, Citizen Science.

Abstrakt

Tato dizertační práce shrnuje sedmiletý vývoj autonomního elektronického systému, určeného pro monitorování zvířat v hnízdních budkách. Tento systém, fungující jako fotopast vestavěná v dřevěné budce, je schopný nahrávat aktivity uvnitř budky na video s vysokým rozlišením, doplněné o řadu dalších údajů. Postupně byly vyvinuty tři verze systému. Model 1.0 bylo bateriové offline zařízení, navržené pro výzkum sýce rousného (*Aegolius funereus*) v jeho přirozeném prostředí. Model 2.0, cílící na monitorování pěvců hnízdících v urbanizované krajině, byl navržen jako zařízení internetu věcí s trvalým připojením k univerzitnímu serveru a napájením ze zásuvky. Model 3.0 byl navržen jako vylepšené řešení, určené pro oba režimy provozu. Aplikace několika desítek zařízení, sloužící jako důkaz proveditelnosti, odhalila enormní potenciál skrytý v kombinaci občanské vědy a internetu věcí, umožňující autonomní sběr bezprecedentního množství biologických dat pro vědecké a edukační účely. Vyhodnocení takového množství dat je výzvou pro budoucí výzkum a vývoj. Tato práce souvisí s odbornými články, publikovanými v impaktovaných žurnálech: Methods in Ecology and Evolution (IF 5.708), Folia Zoologica (0.592) a Ecosphere (2.746).

Keywords: Inteligentní ptačí budka, Fotopast, Pozorovací systém, Internet věcí, Občanská věda.

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List of Acronyms

720p 1280×720 px. 63, 64

CCTV Closed-Circuit Television. 63, 64, 73

CSI Camera Serial Interface. 74

DLNA Digital Living Network Alliance. 76, 78

fps frames per second. 62–64, 69

FTP File Transfer Protocol. 63

GSM Global System for Mobile Communications. 74

IoT Internet of Things. 8–10, 63, 74, 81

IP Ingress Protection. 63

IP Internet Protocol. 76, 77

IR infrared. 62, 63, 65, 72, 73

LAN Local Area Network. 64, 76

LP-WAN Low-Power Wide Area Network. 74

MJPEG Motion JPEG. 63

OS Operating System. 73

PoE Power over Ethernet. 64, 65

px pixel. 62

RFID Radio-Frequency Identification. 62, 75

RTSP Real Time Streaming Protocol. 64, 76

SNBox Smart Nest Box. 1, 3, 62, 64, 65, 67–71, 74–81

SNMP Simple Network Management Protocol. 75

SSH Secure Shell. 76

USB Universal Serial Bus. 63, 73

UVC USB Video Class. 73

VPN Virtual Private Network. 65

Chapter 1

Preface

Camera traps are a common, commercially available tool which is increasingly used for automatic, non-invasive and non-disturbing monitoring of wild animals in their natural environment. Anyway, every off-the-shelf device suffers from some limitations which may be critical for performing desired scientific research. For example, I am not aware of any off-the-shelf camera trap specialized for birds monitoring inside nest boxes. As a result, biological scientists are often forced to construct purpose-designed electronic systems to match their research objectives. That is when they often have to team up with technicians to help them build the system according to their needs. This thesis presents results of such successful, long-term, interdisciplinary cooperation on development and application of an automatic embedded system for cavity-dwelling bird surveillance.

Our cooperation started at the end of 2012. The team was led by biologist Markéta Zárybnická who stated the research objectives, organized and managed all the works. I was responsible for the development of the complete embedded electronic system, called the Smart Nest Box (SNBox). The system hardware was designed and manufactured by Elnico s.r.o., the company of my father where I worked. I personally implemented all SNBox software including drivers, application logic and user interface. The SNBoxes connected to a server created and managed by a server subteam composed of an administrator and web developers. Installation and maintenance of SNBoxes and communication with the applicants were conducted by field technicians and biologists. And the recorded videos were analyzed by many students. In the following text, I use "we" to denote any members of the whole team, not necessarily including me, and "I" only in the context which was solely in my liability.

This thesis does not stand for technical documentation. The main purpose of the thesis is to introduce readers the objectives and results of my PhD study and research activities. The thesis serves as a qualification work necessary for obtaining a PhD title. The thesis text introduces the studied topic and provides three journal papers which I authored or co-authored. Simultaneously, I justify the development of purpose-designed system rather than the use of an off-the-shelf device, describe the key features of the system and decisions that we made during its development, present our experience from application of tens of such devices, show its potential for science and education, and discuss challenges that yet need to be resolved.

The thesis contains 7 chapters. The objectives of my PhD study and research activities are defined in Chapter 2. The introduction to the topic in Chapter 3 is followed by a list of published papers in Chapter 4. The system design is briefly described in Chapter 5, followed by the results of the proof-of-concept applications in Chapter 6. In Chapter 7, unresolved challenges and future system potential is discussed.

Chapter 2

Objectives

The aim of my PhD study and research activities was to design and develop a versatile electronic system embedded in a nest box, forming the SNBox, which could be used for bird-nest monitoring. The core work was highly methodological and purely technical, with real-world effects in science and education in the field of biology.

I aimed to implement a new technology for bird watching allowing the acquisition of high-quality data on animal behaviour for researchers with the possibility of incorporating the public into the application of animal surveillance cameras on a large geographical scale. In particular, I aimed to develop a camera system that would allow i) to live stream and video trap animal activities inside a nest box over the course of an entire year; ii) to collect data on environmental characteristics and the phenotypes of bird species; iii) to remotely acquire the data and store and share these data using Internet connections; iv) to apply the system in both urban and forest areas; v) to involve the public in the application of the camera system and data collection, i.e., using Citizen Science allowing to provide a tight connection between people and their environment; and vi) to apply the system in detached areas under offline, battery-powered operation.

Chapter 3

Introduction

This chapter introduces the reader to our topic by reviewing approaches and technologies related to our work.

3.1 Camera-based surveillance as a non-invasive tool for ecological studies

Visual observations can provide the most detailed insight into animal lives. Camera-based surveillance is a non-invasive, highly sophisticated method for collecting a wide range of biological data on many taxa of animals, extensively applied mainly in last two decades (reviewed by Reif and Tornberg 2006; Trolliet et al. 2014). Camera technologies are most often used for monitoring the trends over time and space in vertebrate populations (estimating population parameters) (e.g. Karanth 1995; Gil-Sánchez et al. 2011; Garrote et al. 2012; X. Liu et al. 2013; Oliveira-Santos et al. 2012; Olson et al. 2012; Gregory et al. 2014), activity patterns in small and large mammals and birds (e.g. Van Schaik and Griffiths 1996; Azlan and Sharma 2006; Zárybnická 2009; Gray and Phan 2011; Oliveira-Santos et al. 2012), behaviour and feeding ecology of nesting birds (e.g. Reif and Tornberg 2006; Grivas et al. 2009; Zárybnická 2009; Zárybnická, Sedláček, and Korpimäki 2009; Zárybnická, Riegert, and Šťastný 2011; Zárybnická, Korpimäki, and Griesser 2012; Zárybnická and Vojar 2013; Colombelli-Négrel and Kleindorfer 2010; Miller, Carlisle, and Bechard 2014), or for the identification of nest predators (e.g. Degregorio, Weatherhead, and Sperry 2014; Liljesthröm, Cingolani, and Roggiero 2014; Praus et al. 2014). This approach is an efficient substitute for standard observational methods, and it especially reduces disturbance of the animals or nests being monitored, gathers audio-visual information during inclement weather or daytime, and significantly saves on human resources and financial costs (e.g. Cutler and Swann 1999). However, despite the great development of technologies, the application of a camera system for animal monitoring still bears some limitations and difficulties. Especially, the duration of recording is limited due to the capacity of both the data storage and the power source; weather conditions, humidity, rain, and dust in particular, limit the functionality of the technical devices; and insufficient light conditions limit the quality of video recordings of (typically) nocturnal animals (e.g. Delaney, Grubb, and Garcelon 1998; Reif and Tornberg 2006; Gregory et al. 2014).

A widely used technique is the autonomous video surveillance system equipped with a camera, power supply (either cable or battery), and a data storage system or direct data streaming capability. In most cases, the video sequence is recorded continuously (i.e. it is "event-independent"), typically with a very low frame rate – time-lapse video (e.g. Colombelli-Négrel and Kleindorfer 2010) or shorter video sequences are recorded periodically with time delays (e.g. Grivas et al. 2009). The disadvantages are the demands on the power supply and the data storage capacity, requiring either a frequent replacement or a sufficient bandwidth of a wired/wireless connection to allow for streaming or downloading the data remotely, which of course poses further demands on the power supply. Often, a large amount of low-value data (i.e. when nothing is happening to the subject) is stored, while a high amount of potentially valuable and interesting events are missing. Another option is to continuously record full audio-visual data and process them manually by watching the recordings in significantly higher speed (e.g. Gula et al. 2010), which allows to speed up data processing, but poses high demands on the viewer's concentration and is generally laborious and prone to human errors.

The alternative approach is an event-triggered video recording, typically activated by an interruption of a light barrier by an animal (e.g. Cutler and Swann 1999; Bosch and Lurz 2014; Trolliet et al. 2014) or motion detector (e.g. Kleintjes and Dahlsten 1992; Franzreb and Hanula 1995). The trigger speed – the time delay necessary for the camera to start shooting once an animal is detected in the camera's zone – can vary from 0.2 sec to more than 4 sec (Trolliet et al. 2014) and is an important parameter when selecting the appropriate system. Event-triggered recording helps us to focus on the ecological data only. In particular, such systems are often used as camera traps (e.g. nest predators, animal presence) or in diet studies (e.g. Kleintjes and Dahlsten 1992; Franzreb and Hanula 1995).

In most used camera systems, the camera resolution and frame rate is insufficient and the trigger speed can be too slow for snapping of fast-moving animals (Trolliet et al. 2014). Moreover, the devices that are used usually work independently on each other without time synchronization and have no power-saving capabilities for periods when the animals are inactive. When the research project requires a mixture of diverse data, the typical approach is the use of multiple single-purpose devices, which are not connected together (e.g. Gula et al. 2010). Such a solution is general, adding a new device to the system is easy, as it means only buying any suitable standalone device on the market. A disadvantage is the maintenance of more devices and high demands on manual data synchronization and post-processing.

3.2 Acoustic expressions play a crucial role in birds ethology

As the acoustic expressions play a fundamental role in the birds ethology (e.g. Kilner, Noble, and Davies 1999; Mello, Vicario, and Clayton 1992; Hasselquist, Bensch, and Von Schantz 1996; Slabbekoorn and Peet 2003), a microphone and audio recorder are a part of a wide range of surveillance systems (e.g. Grivas et al. 2009; Gula et al. 2010). Audio data might be a great benefit of the system, allowing to monitor how the bird fledgelings express their physical state, how they call for food, and how all these acts develop with their age, or how they react to changes of environment.

Besides capturing the intrinsic acoustic expressions, sound reproduction can be used to conduct various studies. For example, Suraci et al. (2017) constructed an Automated Behavioural Response system to perform playback experiments on camera-trapped animals. The system consisted of a camera trap, motion detector and a speaker equipped with an MP3 player, all being commercial off-the-shelf devices connected together. Enari et al. (2017) used loudspeakers as an acoustic allurement to record the presence of sika deers by independent audio recorders. Injaian, Taff, and Patricelli (2018) measured effects of noise pollution by exposing nest boxes of tree swallows (*Tachycineta bicolor*) to the anthropogenic noise produced by an MP3 player connected to speakers with car amplifier and observing birds behaviour by standalone video cameras.

3.3 Monitoring of cavity-dwelling animals requires a specific approach

The camera system design also depends on logistical and practical constraints, in particular on the remoteness and accessibility of nests (Reif and Tornberg 2006). The cavity or hole-using animals are especially difficult to monitor due to hard access to native cavities, which are usually located high up off the ground (Franzreb and Hanula 1995) or underground (Bloomquist and Nielsen 2009). Moreover, the space constraint of the inner part of the cavity limits the installation of monitoring apparatus and poor light conditions inside the cavity hamper high-quality camera monitoring (Bloomquist and Nielsen 2009). Fortunately, many birds (e.g. *Parus major*, *P. caeruleus*, *Sturnus vulgaris*, *Phoenicurus*

phoenicurus, *Ficedula hypoleuca*, *F. albicollis*, *Sitta europaea*, *Strix aluco*, *S. uralensis*, *Glaucidium passerinum*, *Platycercus elegans*, *Aegotheles cristatus*), mammals, including bats (e.g. *Pipistrellus nathusii*, *Plecotus auritus*), squirrels (e.g. *Sciurus vulgaris*, *Glaucomys sabrinus*), dormice (e.g. *Graphiurus murinus*, *Glis glis*), marsupials (e.g. *Gymnobelideus leadbeateri*, *Trichosurus cunninghami*, *Pseudocheirus peregrinus*, *Petaurus breviceps*, *Cercartetus nanus*), as well as reptiles (e.g. *Morelia spilota*, *Varanus tristis*), and insects (e.g. *Vespa crabro*) are willing to use artificial boxes, making them easier to monitor (e.g. Hussey 1997; Ciechanowski 2005; Lindenmayer et al. 2009; Madikiza et al. 2010; Bosch and Lurz 2014).

The artificial boxes provide a wide range of opportunities for the use of animals, for example for breeding (Hussey 1997; Kölliker et al. 1998; Zárybnická, Sedláček, Salo, et al. 2015), roosting (Tyller, Paclík, and Remeš 2012; Mering and Chambers 2014), hibernating (Madikiza et al. 2010), or food storing (Halonen et al. 2007). Especially, bird species using the boxes to breed allow us to study some of the key topics of evolutionary biology, in particular questions about parental care (i.e. the investment of parents to own offspring, which involved preparation of nests and burrows, production of eggs, care for eggs and young, and provisioning of young; Clutton-Brock 1991). Parental care varies across species, and it can be provided by both male and female bird parents or by a single individual (Clutton-Brock 1991). Further, parental care intensity may vary across the breeding season (Podlaszczuk et al. 2014), within nesting phase following the dynamics of nestling demands (C.-J. Liu et al. 2014), and it may also vary with changing food supply (Zárybnická, Sedláček, and Korpimäki 2009), ambient temperature (Conway and Martin 2000), or day length variation (Shaw and Cresswell 2014). Despite quite easy access to the nests located in the boxes and recently available technologies, only a few studies have applied these methods for monitoring and data collection on parental care and nestling development of birds in artificial boxes (but see Kölliker et al. 1998; Wang and Weathers 2009; You et al. 2009).

3.4 Purpose-designed systems allow for unlimited research objectives

Off-the-shelf devices are usually relatively cheap and easy to use. Anyway, their functionality is imperfect. Apps and McNutt (2018) performed a rigorous, realistic test of commercially available camera traps, finding that all models have some dead detection zones, the trigger delay for video recording can be significant, and smaller animals are more likely to be ignored than bigger animals. Additionally, the functionality of off-the-shelf devices is naturally limited to a particular task, which leads the researchers to the need to combine multiple devices to reach their research objectives. Use of multiple standalone (i.e. unsynchronized) devices (e.g. Gula et al. 2010; Enari et al. 2017; Injaian, Taff, and Patricelli 2018) is a simple approach counterbalanced by compromises, e.g. complicated data post-processing. To achieve required operation, some researchers develop additional purpose-designed components that somehow adjust, extend or synchronize functionality of the standard off-the-shelf components (e.g. Bezouška, Děd, and Drdáková 2005; Suraci et al. 2017). Anyway, to accomplish real freedom with stating research objectives independent of capabilities of commercial, off-the-shelf devices, researchers are often forced to develop complete purpose-designed systems, using custom electronics (e.g. Grivas et al. 2009) or general-purpose single-board computers (e.g. Prinz et al. 2016).

3.5 Internet of Things allows to collect ecological data automatically

The term "Internet of Things" (IoT) resonates in the technological world for a couple of years already. Nord, Koohang, and Paliszkiewicz (2019) reviewed many publications concerning this topic, concluding that there are many definitions of the term, yet none of them was standardized. For example, International Telecommunication Union recommends defining IoT as "a global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies" (ITU-T Y.2060 2012). Madakam, Ramaswamy, and Tripathi (2015) suggest the best definition to be "an open and comprehensive network of intelligent objects that have the capacity to auto-organize, share information, data and resources, reacting and acting in face of situations and changes in the environment". Apparently, comprehensive definitions are not always comprehensible. I would imprecisely describe IoT as a trendy name for the goal of the ongoing process of interconnecting all electronic devices into a global network of both living and inanimate objects. The paradigm shift from the "old Internet" to the "Internet of Things" can be summarized by the idea that the first version of the Internet was about data created by people, while the next version is about data created by things (Madakam, Ramaswamy, and Tripathi 2015).

IoT market statistics and predictions vary across sources but vital grow expectations are common to all of them. IoT Analytics (2018) reported 10.8 billion non-IoT devices (PCs, laptops, mobile phones) and 7.0 billion IoT devices ("things") in 2018. They predict the equal number of IoT and non-IoT devices (11.6B vs. 11.6B) in 2021 and almost twice the number (21.5B vs. 12.7B) of IoT devices compared to non-IoT devices in 2025 (see Fig. 3.1). The IoT market is forecasted to tenfold within 7 years, from $151B in 2018 to $1,567B in 2025. IoT is expected to rule the future of the Internet and enter every domain of human lives. IoTization (the process of IoT incorporation) of various fields has led to the creation of industry-specific names as Industry 4.0 (factories), Smart Home (households), Smart City (cities), Smart Grid (electricity), Smart Farm (agriculture), or Smart Earth (environment).

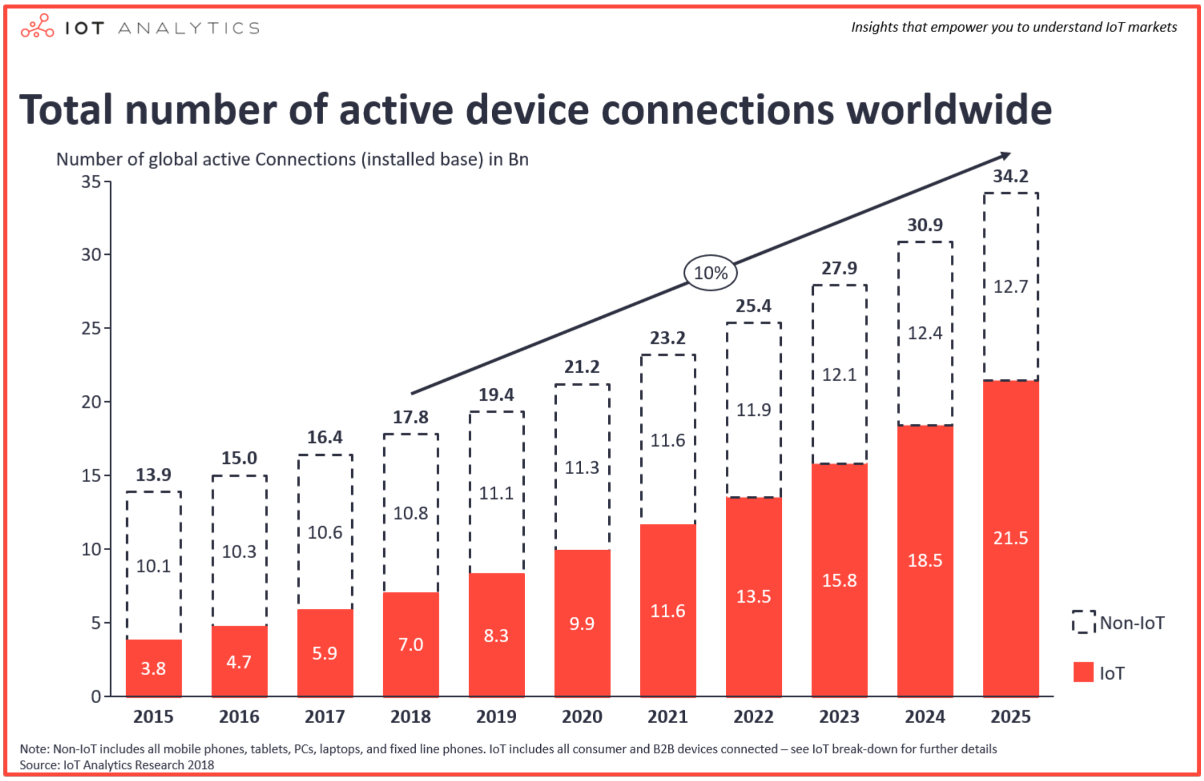

Figure 3.1: The IoT market is predicted to grow rapidly (IoT Analytics 2018).

Smart Earth denotes the set of environmental applications of the Internet of Things, i.e. a network of (automatic) environmental sensors and actuators. This involves terrestrial, aquatic, and aerial sensors, satellites, and monitoring devices, including wearables and biotelemetric technologies devised for both humans and animals (Bakker and Ritts 2018). Smart Earth applications cover all areas of environment-related problems. For example, Snyder et al. (2013) describe the ongoing change of air pollution monitoring methods from sparse, expensive, complex meteorological stations to a dense network of lower-cost, easy-to-use, portable air pollution monitors (sensors) providing frequent data in near real-time. Zheng et al. (2018) developed a distributed wireless system for long-term real-time ecological monitoring and analysis of conditions in forest areas to provide early warnings on local forest fires. Save the Elephants (n.d.), a British research and conservation organization, developed a virtual fence around Kenyan natural reservations and equipped the elephants known for crop-raiding by GPS trackers. Whenever an elephant crossed the virtual fence, nearby farmers were warned by an SMS to chase the elephant before it made significant damage. Zoological Society of London (n.d.) developed Instant Detect, a satellite-connected camera trap with acoustic sensors to detect humans and wildlife, and installed it in Kenya where it helps the rangers in the fight against poachers by providing an early warning system of illegal activity.

Smart Earth applications enable automatic aggregation of unprecedented streams of environmental data. The amount and timeliness of the data will completely transform environmental science and governance in the future as this will allow real-time analyses of abundant contextual data and potentially immediate actions. The challenges that yet need to be resolved include connectivity (billions of devices with worldwide coverage), big data handling (safe, secure and accessible storage of terabytes of data) and automatic processing and analysis (manual evaluation is a no go) (Bakker and Ritts 2018).

3.6 Citizen Science as a tool for citizen-driven research and public education

Citizen Science is a concept that incorporates the public to actively participate in scientific projects. Although Citizen Science is generally not conditioned by any technical means, improved connectivity and growth of IoT accelerates exploitation of Citizen Science projects.

Citizens can play a role of “sensors” or observers, i.e. data providers allowing to gather high volumes of data over large temporal and spatial scope. For example, Goodchild (2007) discusses the effects of citizens participating on creating and improving geographical data for Wikimapia or OpenStreetMap platforms, and Sullivan et al. (2009) describe eBird, a successful program engaging a vast network of human observers to report bird observations.

Citizens can further play the role of field workers that perform, besides other tasks, installation and maintenance of the infrastructure. For example, the Michigan Bluebird Society (n.d.) exploits the power of citizens to install and regularly check bluebird nest boxes. McShea et al. (2016) used volunteers to deploy hundreds of camera traps for mammal monitoring across six contiguous U.S. states and to regularly upload the photos from the memory cards using eMammal cyberinfrastructure.

Citizen Science projects, unlike crowdsourcing, are specific for employing a community with some extent of the field knowledge, allowing to incorporate it in some intellectual tasks. For example, bird watchers engaged in the eBird program were expected to identify the observed birds (with the assistance of a mobile application), and volunteers in the eMammal project were asked to tag the content of the photos before uploading.

The key to the success of Citizen Science projects is the motivation of the volunteers, based on their feeling that their work is meaningful. For example, the eMammal participants were equally excited for the opportunity to photograph wildlife (22 % of responders), as they were to contribute to science (22 % of responders) (McShea et al. 2016). Similarly, eBird engaged the birders for giving them a tool to promote their hobby activity to a scientific effort, providing information on species occurrence, migration timing, and relative abundance at a variety of spatial and temporal scales (Sullivan et al. 2009). Additionally, such engagement has an important educational side-effect, as the contributors voluntarily learn more about the ecological domain, interact with experts and improve their skills. As a result, Citizen Science has proven to be a great tool for both formal and informal public education (Borden et al. 2013).

3.7 Machine Learning as a tool for processing of high volumes of ecological data

Computer vision and machine learning show high potential in processing of huge amount of ecological data captured in camera-trapping studies. This rapidly growing area has been reviewed by Weinstein (2018). The review involved 187 articles, reporting consistent growth of computer vision applications in ecological studies over time. The reviewer identified three groups of applications according to the most common tasks for ecological computer vision: description, counting and identity.

The description is understood as the qualification of the object of interest, e.g. animal colouration, patterning or size. For example, Stoddard, Kilner, and Town (2014) developed a computer vision tool for analyzing visual patterns, called NaturePatternMatch, and applied it to the study of egg pattern signatures. The images were calibrated to correspond to the bird luminance vision. The authors found that the bird species that are most frequent targets of common cuckoo (*Cuculus canorus*), that sneaks its mimetic eggs to their nests, have evolved the most recognizable egg patterns to defend against such forgery.

Counting is understood as the detection and enumeration of the objects of interest within the image. That usually involves segmentation, i.e. separation of the foreground from the background, using background subtraction, where the background model is created from a set of subsequent video frames. Such a general approach has been in use for many years already. For example, Spampinato et al. (2008) successfully used a machine vision system for counting fish in low-quality underwater videos, achieving an overall accuracy as high as 85 %. Tailoring detection algorithms by training the model to a particular species can further improve accuracy significantly. For example, Zeppelzauer (2013) achieved detection accuracy of elephants in wildlife video between 94 % and 97 %.

Segmentation of static objects, e.g. eggs, cannot be solved by general algorithms, it always has to be tailored to the particular task. An example of (silkworm) egg-counting algorithm is presented by Pandit et al. (2015).

Identity is understood as the classification of an individual or species based on its appearance. For example, Yu et al. (2013) developed a machine vision algorithm for automated identification of animal species in camera trap images of mammals in a rainforest. Although the algorithm was not tailored by any apriori knowledge like biometric features, they reached decision precision on 18 species over 80 %. Species classification can be practically used in public applications, too. A great example is Merlin, a bird identification application for Android and iOS (Farnsworth et al. 2013), created by Visipedia and the Cornell Laboratory of Ornithology. It uses Google's TensorFlow deep learning platform to identify bird species captured by the user's mobile phone camera. Individual re-identification is a common subtask of a range of studies, either for tracking individuals in the study area or for population estimates studies. Quality of re-identification from camera trap images has been growing over the last 30 years by incorporating computer vision. Modern algorithms, based on machine learning principles, can reach an accuracy of around 90 % (Schneider et al. 2019).

Chapter 4

Publications

This chapter presents full content of all related publications that I authored or co-authored in impacted journals. The papers are listed in the logical order instead of ordering by date of publication.

1. **Zárybnická, Kubizňák, et al. 2016**: Methods in Ecology and Evolution (IF 5.708[1])
   Chapter 4.1 on page 15.
2. **Šindelář, Kubizňák, and Zárybnická 2015**: Folia Zoologica (IF 0.592[2])
   Chapter 4.2 on page 27.
3. **Kubizňák et al. 2019**: Ecosphere (IF 2.746[3])
   Chapter 4.3 on page 35.

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[1] Impact Factor in 2016.
[2] Impact Factor in 2015.
[3] Impact Factor in 2018.

4.1 Zárybnická, Kubizňák, et al. 2016

M. Zárybnická, P. Kubizňák, et al. (2016). “Smart nest box: A tool and methodology for monitoring of cavity-dwelling animals”. In: *Methods in Ecology and Evolution* 7.4, pp. 483–492. ISSN: 2041210X. DOI: `10.1111/2041-210X.12509`

Methods in Ecology and Evolution British Ecological Society

Methods in Ecology and Evolution 2016, **7,** 483–492 doi: 10.1111/2041-210X.12509

Smart nest box: a tool and methodology for monitoring of cavity-dwelling animals

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Summary

1. Camera recording and video analysis have emerged as a successful non-invasive method for collecting a wide range of biological data on many different taxa of animals. However, camera monitoring has rarely been applied to long-term surveillance of cavity or box-nesting species and ordinary off-the-shelf cameras are employed.

2. We present methodology and data on the effectiveness of nest box monitoring using a camera system embedded in four 'smart nest boxes' (SNBoxes). We applied the SNBoxes to eight Tengmalm's owl (*Aegolius funereus*) nests in the Czech Republic during a 5-month period in 2014. Each SNBox consisted of a pair of cameras with infrared lighting, an event detector, a radiofrequency identification reader, auxiliary sensors and a 60 Ah 12 V battery to power the whole system. All devices used were centrally managed by an embedded computer with specifically developed software.

3. Using four SNBoxes, we observed owl nesting continually during the incubation, nestling and fledgling phases, in total 309 days, resulting in 3382 owl video events. Batteries were changed every 6·5 days. A memory of 4 GB was found sufficient to store monthly data. We identified 12 types of male and female parental activities and their timing, the diet composition and frequency of prey delivery, the manner of prey storage, the light intensity at the time of each parental activity, the temperature inside the clutch and outside the box and the duration of nestling period of each young. We also produced a video on owl nesting for the general public.

4. The SNBox and related methodology show enormous potential as a non-invasive tool for monitoring animals using boxes or natural cavities. The main advantage of the SNBox is the possibility to study both nocturnal and diurnal animal species and great flexibility in use of the software and hardware for different tasks. As a result, the SNBox provides an opportunity for novel insights into the breeding, roosting, hibernating, and food storage activities of a wide range of cavity-living birds, mammals and reptiles.

Key-words: animal activity, camera monitoring, cavity, event detector, hole, infrared light, nest box, non-invasive method, parental care, RFID reader

Introduction

Camera-based surveillance is a non-invasive method for collecting data on many taxa of animals (reviewed by Reif & Tornberg 2006; Trolliet *et al.* 2014). Camera technologies are most often used for monitoring the trends over time and space in vertebrate populations (e.g. Gregory *et al.* 2014), their activity patterns (e.g. Gray & Phan 2011), behaviour and feeding ecology (e.g. Miller, Carlisle & Bechard 2014), or for the identification of nest predators (e.g. DeGregorio, Weatherhead & Sperry 2014). This approach is an effective substitute for standard observational methods, and it especially reduces disturbance of the animals or monitored nests. It also allows to gather information during inclement weather or time, and saves on human resources and financial costs (Cutler & Swann 1999). However, despite technological advancements, application of camera systems for animal monitoring continues to have its limitations and difficulties. Especially, data storage and power source limit the duration of recording; weather conditions, humidity, rain and dust limit the functionality of the technical devices; and insufficient light limits the quality of video recordings of nocturnal animals (Delaney, Grubb & Garcelon 1998; Reif & Tornberg 2006). Moreover, the camera systems used usually work without time synchronization with other devices (e.g. data loggers) and without power saving when the animals are inactive.

The camera system design usually depends on logistical and practical constraints, in particular on the remoteness and accessibility of nests (Reif & Tornberg 2006). Cavity or hole-using animals are especially difficult to monitor due to accessibility difficulties of natural cavities, which are usually located high up off the ground (Franzreb & Hanula 1995) or underground (Bloomquist & Nielsen 2009). Moreover, the space constraints in cavity interiors hamper the installation of monitoring apparatus. Fortunately, many birds, mammals, as well as reptiles, and insects are willing to use artificial boxes, making

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them easier to monitor (see Appendix S1 for detailed information, Supporting Information).

Artificial boxes provide a wide range of opportunities for animal use, including breeding (Kölliker *et al.* 1998), roosting (Tyller, Paclík & Remeš 2012), hibernating (Madikiza *et al.* 2010) or food storing (Halonen *et al.* 2007). In particular, bird species using the boxes to breed allow us to study some of the key topics of evolutionary biology, especially questions about parental care (i.e. parental investment in offspring, which involves egg laying, incubation and provisioning of young; Clutton-Brock 1991). Parental care intensity may vary during the breeding season (Podlaszczuk *et al.* 2015), with increasing nestling age (Liu *et al.* 2014), changing food supply (Zárybnická, Sedláček & Korpimäki 2009), ambient temperature (Conway & Martin 2000) or day length variation (Shaw & Cresswell 2014). However, few studies have applied camera systems for monitoring and data collection to parental care and nestling development of birds breeding in artificial boxes.

In this study, we report on the suitability of an electronic hardware and software design for collecting data on parental care and feeding ecology in cavity-nesting bird species. Specifically, we applied the technology to Tengmalm's owl (*Aegolius funereus*) – the strictly nocturnal species with divided parental duties during nesting (e.g. Zárybnická, Korpimäki & Griesser 2012). We monitored eight owl nests using four 'smart nest boxes' (SNBoxes) in the wild. We aimed at these specific objectives: (i) to create a camera system that would work for 6–8 days without replacement of the battery, with sufficient data memory capacity, and with the possibility to set the awake time of the system according to actual sunset/sunrise timing, including assessment of the battery longevity in such arrangement, (ii) to document entire nesting process, including specific parental care and develop a short promotional video on owl nesting, (iii) to identify the diet composition of prey delivered by individual parents to the nest, (iv) to evaluate the frequency and timing of parental activities in relation to the nestling age and the interseasonal variability in sunset and sunrise timing, including changes in outdoor light intensity at time of parental activities during the breeding season (i.e. from April to August) and (v) to evaluate the effect of outdoor temperature on time spent by the female outside the clutch and the consequent decrease in temperature inside the clutch.

Materials and methods

STUDY SITE

We conducted the study in the Ore Mountains, in the northern part of the Czech Republic (50°N, 13°E), in habitat composed of Norway spruce (*Picea abies*) forests, secondary growth of young trees (mainly non-native prickly spruce, *Picea pungens*), open areas, and solitary trees (mostly European beech, *Fagus sylvatica*). In this habitat, Tengmalm's owl breeds primarily in artificial nest boxes (>90% nests), as natural cavities can only be found rarely in solitary beech trees (Zárybnická *et al.* 2015a). We installed nest boxes to provide nest-sites for Tengmalm's owl in this area since 1999 under the project of the Czech University of Life Sciences Prague. The number of installed boxes varied from 100 to 212 in different years during 1999–2014 (133·9 ± 8·4 boxes per year, an area of 100 km^2). Tengmalm's owl used to breed from 10 to 26 boxes every year (12·6 ± 1·5% of installed boxes per year). We made all boxes manually of raw wooden boards (20 mm thick) with dimensions of 250 × 250 × 400 mm, and filled up with wood chips. The distance from the top of the layer of wood chips to the box entrance was 220–240 mm, and the diameter of the opening was 80 mm. We typically installed the boxes at a height of 3–5 m above the ground, and we regularly repaired, cleaned and relocated them.

FIELD PROCEDURES

We conducted the present study between April and August 2014. In this year, 212 nest boxes were available for Tengmalm's owl. We inspected all nest boxes at intervals of 1–3 weeks, to detect new breeders. We replaced ongoing nesting in the regular nest boxes with SNBoxes (the design described below). Throughout the study period, we found a total of ten nests; eight of which we monitored by four SNBoxes (two sequential nests per SNBox). We monitored five nests from the incubation to fledgling phase, and other three nests from the hatchling to fledgling phase. We checked the nests weekly to measure, weigh and ring the nestlings, and we also chip-ringed the adult females.

DESIGN OF THE SMART NEST BOX

We mention here only main characteristics of the SNBox, detailed hardware and software information is available in Appendix S2. We designed the SNBox as a regular nest box augmented with additional space for embedding all the required components (Fig. 1a). The overall dimensions of the SNBox were 320 × 250 × 820 mm, and the weight was 15 kg (without the battery). Most of the outer box surface was covered with an aluminium plate to protect against nest predation by pine marten (*Martes martes*) (Fig. 1b). The SNBox electronics consisted of a control board (computer, Fig. 2a), a pair of cameras with infrared lighting (with a peak wave length of 830 nm, Fig. 2b), an event detector (Fig. 2c), a radiofrequency identification reader, auxiliary sensors and a 60 Ah 12 V battery to power the whole system.

We designed the control board with a dual-core processor to run two operating systems in parallel, a 256 MB operating memory, and both Ethernet and Wi-Fi integrated circuits (the latter was not available during the study). We used a 4 GB micro SD memory card to store the output video records and metadata, and a Linux FTP server to fetch the data over the Ethernet cable.

We used two USB monochromatic industrial cameras, without an IR-cut filter, that provided the video in resolution of 1280 × 1024 pixels, with up to 10 frames per second (fps). We placed the 'door camera' on the back side of the box (opposite the SNBox opening), and the 'floor camera' on the ceiling of the box, allowing a view of the nest box floor (Fig. 1a).

We designed an event detector in the form of an IR light barrier consisting of an IR light beam transmitter and a receiver set opposite the transmitter. We assembled the device on a U-shaped board and placed it in the SNBox opening (Fig. 2c).

In Tengmalm's owl, it is difficult to distinguish between males and females. For easier recognition of individuals, we equipped female parents with RFID tags fixed to their legs (chip ring). We used a 125 kHz RFID reader module, and a custom circular antenna embedded in a groove around the SNBox opening to scan the tags. At the moment when a female passed through the opening, the tag was scanned and its unique numerical ID was stored as part of the simultaneously triggered video event.

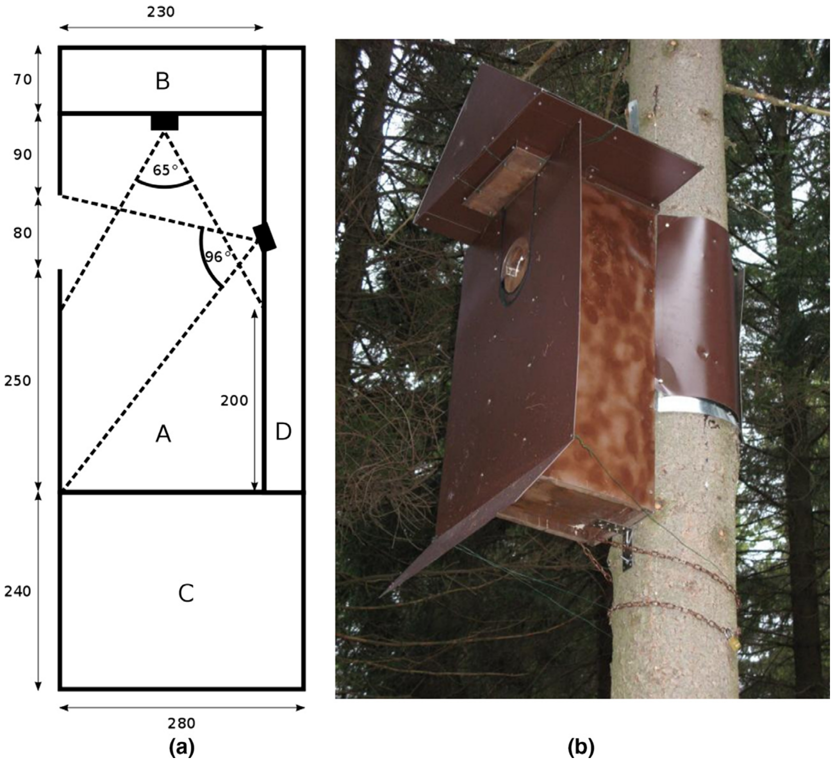

Fig. 1. (a) Design of the smart nest box (SNBox) and its individual parts: (A) nesting area; (B) electronic area – located in the top part of the box, used for storing the control board; (C) battery area – located on the bottom of the box; and (D) the wiring area – located on the back side of the box. Dimensions are shown in millimetres. (b) Application of the SNBox in the field. Note that most of the outer box surface was covered with aluminium plates and equipped with an extended front plate and a gabled roof to protect against pine marten predation.

We used interior and exterior temperature sensors, with ±0·25°C accuracy, and an exterior light sensor that yielded dimensionless numbers from 0 to 4095 (i.e. light intensity index). We attached the exterior device to the casing of the SNBox and embedded the interior device in a groove on the bottom of the SNBox. The values were measured both every 30 seconds and at the moment of every owl activity event.

We developed a special software for central management of all devices used (Fig. S1). We designed the software such that the door camera was activated by the interruption of the IR light barrier and worked for 5 s, while the floor camera was activated at the moment when the door camera stopped recording and worked for 30–120 s (depending on the user settings). The frames from each camera were stored in a fast volatile memory (110 MB) in the raw image format (pgm, Portable Graymap) and later compressed into two avi video files, one for each camera. We reduced the trigger speed, that is the time delay between disruption of the light barrier by the owl entering the SNBox opening and triggering the first camera frame, to 16 ms.

We designed the system to switch between a sleep and awake mode. During the sleep mode, the cameras, light barrier and RFID reader were powered off, while during the awake mode all peripherals were powered on. Because Tengmalm's owl is active only during night-time and the night length varies up to four hours from April to August in the Central Europe, we set an awake time of the system after each 6–8 days (when the battery was changed) according to actual sunset and sunrise.

We developed a user interface for the system, that is a set of equipment that allowed the user to interact with the system, download recorded data and adjust the settings. We strictly defined the structure of the accessible file system consisting of 4 top-level directories. The 'config' directory contained two configuration files, allowing us to customize the camera properties (exposure, signal gain), video properties (duration, frame rate) and power-saving settings (start and end of the awake time). The 'data' directory stored the video records, each event in an individual subdirectory named by respective timestamp (with an accuracy of one-second). Each such subdirectory contained the video files and a text file with metadata (temperature and light conditions, scanned RFID code, exact date and time). The 'sensors' directory contained text files and stored the climate conditions (temperature, light). The 'log' directory contained numerous files with the system debug logs, for development purposes.

VIDEO ANALYSIS PROCESS

After collecting all data in the field, we extracted biological information available in the 'data' directory into Microsoft Office Excel spreadsheet. First of all, we recorded the date and time of each owl activity, sex of the owl parent, temperature inside the clutch and outside the SNBox, and light intensity outside the SNBox. Afterwards we analysed each 'video event' which included two video records made by two cameras. From the door camera, we checked visually whether the owl parent arrived or departed the SNBox, if the parent brings the prey or not, the type of prey, and if the prey was decapitated or not. Video recording captured by floor camera provided us additional information on the number of eggs and nestlings, and the location of the stored prey inside the box.

STATISTICAL ANALYSES

We performed all statistical tests with generalized linear mixed models (GLMM) using *lmer* function in R statistical software, version 3.02 (R Development Core Team 2011). Statistical significance was obtained by comparing each model with a relevant previous model using the ANOVA command. Factors were added to the model based on the Akaike's information criterion. The values of chi-squared statistics were shown. First, we tested the effect of the night length on the voltage decrease of battery. We used Gaussian distribution of a dependent variable, and individual battery as a random factor. We further tested the effect of the nestling age (expressed as the number of days since egg laying) on the time spent by females outside the nest and the number of prey items delivered by males. We used quasi-distributions of dependent variables, the day in the season (i.e. the number of days since January 1) as a covariate, and nest as a random factor. We also tested the effect of intraseasonal variability in sunset and sunrise timing on timing of prey delivery by males and females leaving the nest. We used quasi-distributions of dependent variables, and nest as a random factor. Further, we tested the effect of a month (April–July) on the outdoor light intensity (measured as light intensity index) at time of prey delivery by males and females leaving the nest. We used quasi-distribution of dependent variable, and nest as a random factor. We performed *post hoc* comparisons using *glht* function. Finally, we tested the effect of outdoor temperature on time spent by female outside the nest, as well as the effect of both temperature outside the SNBox and time spent by female outside the nest on the decrease of temperature in the clutch during female absence (i.e. difference in temperature of the clutch between female departure from the nest and female entering the nest). We used Gaussian distributions of dependent variables, and nest as a random factor. All values are reported as means ± SE.

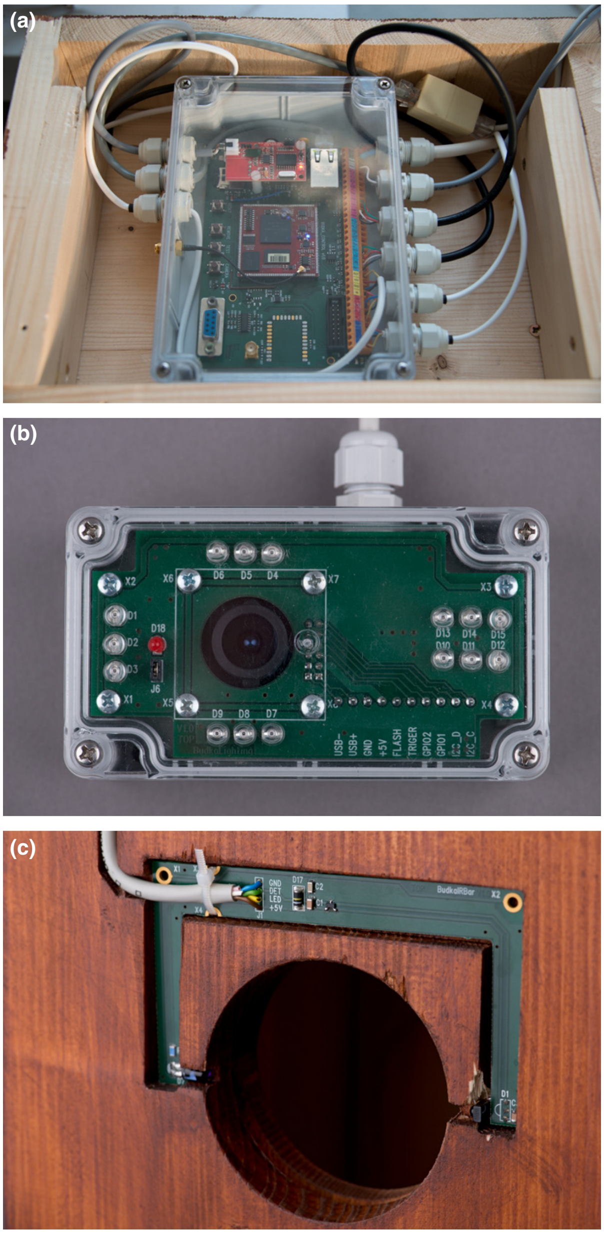

Fig. 2. Components of the smart nest box (SNBox): (a) the connected and housed control board, placed in the top area of the SNBox; (b) the camera with a lighting board, housed in a box with a transparent cover; (c) infrared light barrier, laid in a shallow groove in the front of the SNBox. During the SNBox application, it was hidden by a thin wooden cover.

Results

TECHNOLOGICAL INFORMATION

We changed the batteries on average every 6·5 days (SE = 0·15, $N = 56$). We measured 13·0 ± 0·02 V ($N = 56$) at the time of connecting the battery to the camera system and 12·1 ± 0·02 V ($N = 56$) at the time of disconnecting the battery. The battery was never fully discharged at the time of disconnection. The voltage decrease of the battery varied during the breeding season depending on the night length ($\chi^2 = 10{\cdot}9$, d.f. = 48, $P < 0{\cdot}001$, Fig. 3).

Depending on the total number of recorded events and the configuration of video parameters, the recordings required different amounts of memory space. The highest registered amount of space used for data collected in a 1-week period was 890 MB. The typical configuration, 5 s of 10 fps video recorded by the door camera and 60 seconds of 4 fps video recorded by the floor camera, led to use of about 101 MB of the 110 MB fast temporary memory.

Downloading the data recorded during each period took us about 5 min. Maintenance of one SNBox, including all related operations (battery replacement, nestling measurements, bird ringing, checking of stored prey, etc.), took about one hour

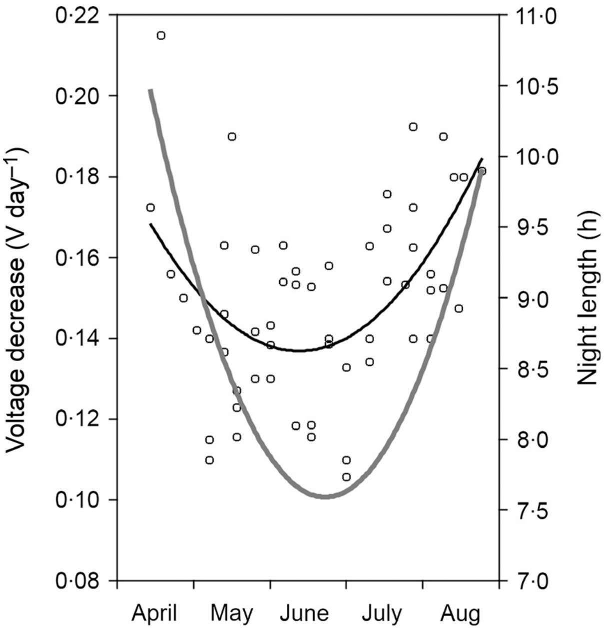

Fig. 3. Changes in power consumption of the smart nest box, expressed by the voltage decrease of a 60 Ah 12 V traction battery per a day, during the breeding season (i.e. from April to August). Row data are presented. Night length is fitted by grey line, battery consumption by black line.

every 6–8 days. At the end of the season, after collecting data from eight nests, we analysed the video data by one person in 60 h total.

The sensors did not work on 38 out of a total 309 days when the SNBoxes were applied (this problem involved three SNBoxes applied to five nests), and the RFID codes were not successfully scanned in 26·4% of all bird passes (four SNBoxes applied to eight nests).

The cost of one SNBox, including the wooden box and all electronics reached €1,000, without taking the development costs into account.

BIOLOGICAL INFORMATION

During 309 days of the data collection (38·6 ± 4·2 days per nest), we recorded a total of 3382 owl video events (422·8 ± 47·2 events per nest, and 10·9 ± 0·3 events per day, respectively), and only one video event without any owl activity. We identified a total of 2761 owl parental activities (345·1 ± 54·6 activities per nest), which we categorized into 12 types (Table 1). We made an original video containing unique information on owl nesting (Video S1).

None of the Tengmalm's owl parents deserted the nest after initiating use of the SNBox. However, male parents showed partial perception of the glow from the IR light source during the first days after camera installation. In particular, they usually escaped of the glow from the IR light at the moment when they entered the SNBox opening and the camera system was triggered. It resulted in their immediate escape from the nest opening without delivering the prey to the female (Video S2). The proportion of realized prey deliveries, that is the male handed over the prey to the female, increased with the number of monitored days (1st day: 27·5 ± 6·4%, 2nd day: 43·4 ± 5·4%, 3rd day: 66·7 ± 12·8%, 4th day: 100%). All males adapted to the glow of IR light, that is they realized all prey deliveries, on average 1·9 ± 0·7 days after SNBox application.

We found that females incubated eggs and brood nestlings continually, leaving the nests only for a few minutes per night, while males provided most of the food (more than 94%) during the incubation and nestling phases (Table 1). We recorded three types of parental behaviour of Tengmalm's owl that were not previously documented. First, males never threw a prey inside the SNbox. Instead, they handed over each prey directly to the female or the young, typically from bill to bill (Figs. 4d–f, Video S1). Secondly, when the young reached the fledgling phase and the female was absent from the nest, males sometimes visited the SNBox with a prey item, but they did not give the prey directly to the fledglings. Instead, they stayed usually 1–3 s holding the prey in the bill displaying it to their fledglings, and then flew away, still holding the prey. This activity was rarely recorded in females (Table 1). Thirdly, in five cases (four shrews and one bird), the female staying inside the SNBox took the prey from the male and then she left the nest with this prey (Fig. 4b). At this time, other prey items (3·8 ± 1·0 prey items), eggs (1·8 ± 0·9 eggs) and nestlings (1·6 ± 0·7 nestlings at age of 4·7 ± 1·2 days) were present at the nest. A few minutes later, the female came back to the nest without the prey.

Every time when the female left the SNBox, we were able to check the content of the nest using the camera images (Fig. 4a, c). We found eight females laid in total 29 eggs (3·6 ± 0·2 eggs per nest), 22 of which hatched (2·8 ± 0·5 eggs per nest), and 17 fledglings left the SNBoxes (2·1 ± 0·4 fledglings per nest). Young stayed in the nests for a period of 29–36 days (32·2 ± 0·8 days), and they left the SNBoxes during different

Table 1. Types and numbers of Tengmalm's owl parental activities recorded using smart nest boxes (SNBoxes). Eight sequential nests were monitored by four SNBoxes

	Male		Female	
Type of parental activity	Number of activities	% of total activities	Number of activities	% of total activities
Entering the SNBox opening with prey, giving the prey to nestlings or the female (from bill to bill)*, and leaving	1062	72·4	56	4·4
Entering the SNBox opening without prey, and leaving	19	1·3	21	1·6
Entering the SNBox with prey, giving the prey to nestlings, and leaving	253	17·2	12	0·9
Entering the SNBox with prey, and leaving with the same prey*	133	9·1	3	0·2
Entering the SNBox without prey, and incubation or brooding			471	36·4
Interruption of incubation or brooding, and leaving the SNBox without prey			466	36·0
Interruption of incubation or brooding, and leaving the SNBox with prey*			5	0·4
Peeping out of the SNBox during incubation or brooding			260	20·1
Total	1467	100	1294	100

*Previously undocumented parental activities.

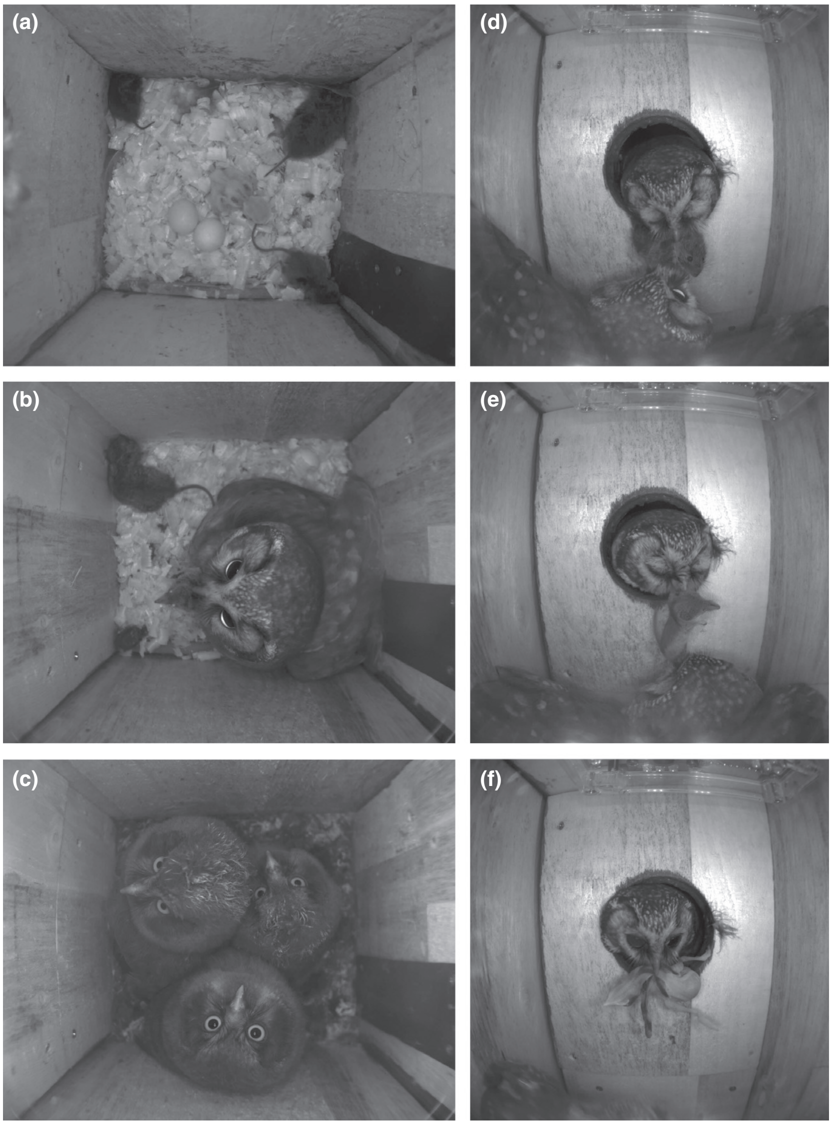

Fig. 4. Nesting of Tengmalm's owl photographed by the camera system of the smart nest box (SNBox): (a) stored prey, eggs and hatchlings in the nest; (b) the female with a shrew (Soricinae) preparing to leave the nest; (c) fledglings at the nest; (d) the male in the SNBox opening giving a prey item (Arvicolinae) to the female; (e) the male in the SNBox opening giving a prey item (Soricinae) to the female; (f) the male in the SNBox opening giving a prey item (bird nestling) to the female.

times (4 fledglings between 8 and 9 PM, 6 between 9 and 10 PM, 5 between 4 and 5 AM and 2 between 7 AM and 8 PM).

We recorded 1448 prey deliveries by males and 76 deliveries by females in eight nests (Table 2). Of all prey items delivered, we identified 71·2% as mammals and 26·8% as birds. We did not identify 2·0% prey items. We further identified 98·1% of all mammals as Arvicolinae (Fig. 4d), Murinae, Soricinae (Fig. 4e) and Gliridae (Table 2). Among birds, we were able to distinguish 25·2% to genus or species level, and 84·8% to age (adult or juvenile, Fig. 3f). We further recorded that 14·7% of all prey items delivered to owl nests were decapitated. Moreover, females nearly always (>95% of cases) stored the prey side-by-side, with their heads in the corner (Fig. 4a).

Time spent by females with nestlings decreased ($\chi^2 = 260948$, d.f. = 460, $P < 0{\cdot}0001$, Fig. 5a), while the number of prey delivered by males increased ($\chi^2 = 10{\cdot}51$, d.f. = 282, $P = 0{\cdot}001$, Fig. 5b), with increasing age of the nestlings. Simultaneously, both male and female owls adjusted their activity according to sunset and sunrise timing (females: $\chi^2 = 2548{\cdot}3$, d.f. = 469, $P < 0{\cdot}001$, males: $\chi^2 = 32011$, d.f. = 1441, $P < 0{\cdot}001$, Figs. 5c,d), and outdoor light intensity index at time of parental activity did not differ significantly among months (females: P at least 0·288, males: P at least 0·052).

The temperature inside the clutches ($N = 5$) dropped by 0·25–9·00°C (3·22 ± 0·17°C per female leaving, $N = 147$) during female absence, and this temperature drop increased with both increasing time spent by female outside the nest and decreasing outdoor temperature ($\chi^2 = 19{\cdot}90$, d.f. = 141, $P < 0{\cdot}0001$, Fig. 6). Finally, females reduced the time spent outside the clutch with decreasing outdoor temperature ($\chi^2 = 78{\cdot}82$, d.f. = 141, $P = 0{\cdot}02$, Fig. 6).

Discussion

TECHNOLOGICAL INFORMATION

We created a system that worked for a week without replacement of the 60 Ah 12 V battery and with sufficient data

Table 2. Diet composition of prey items delivered to the nests (N = 8) by male and female Tengmalm's owls identified using the camera system of the smart nest box

	Male		Female	
Prey species/group	Number of prey items delivered	% of total prey items delivered	Number of prey items delivered	% of total prey items delivered
Mammals				
Murinae	101	7·0	10	13·2
Arvicolinae	420	29·0	26	34·2
Soricinae	463	32·0	30	39·5
Gliridae	14	1·0		
Unidentified mammals	20	1·4	1	1·3
Birds				
Erithacus rubecula	11	0·7		
Turdus sp.	18	1·2		
Sylvia atricapilla	13	0·9		
Phylloscopus sp.	37	2·5	2	2·6
Ficedula sp.	1	0·1		
Parus sp.	13	0·9	2	2·6
Fringilla sp.	5	0·3		
Carduelis chloris	1	0·1		
Unidentified birds	301	20·8	5	6·6
Unidentified prey	30	2·1		
Total	1448	100	76	100

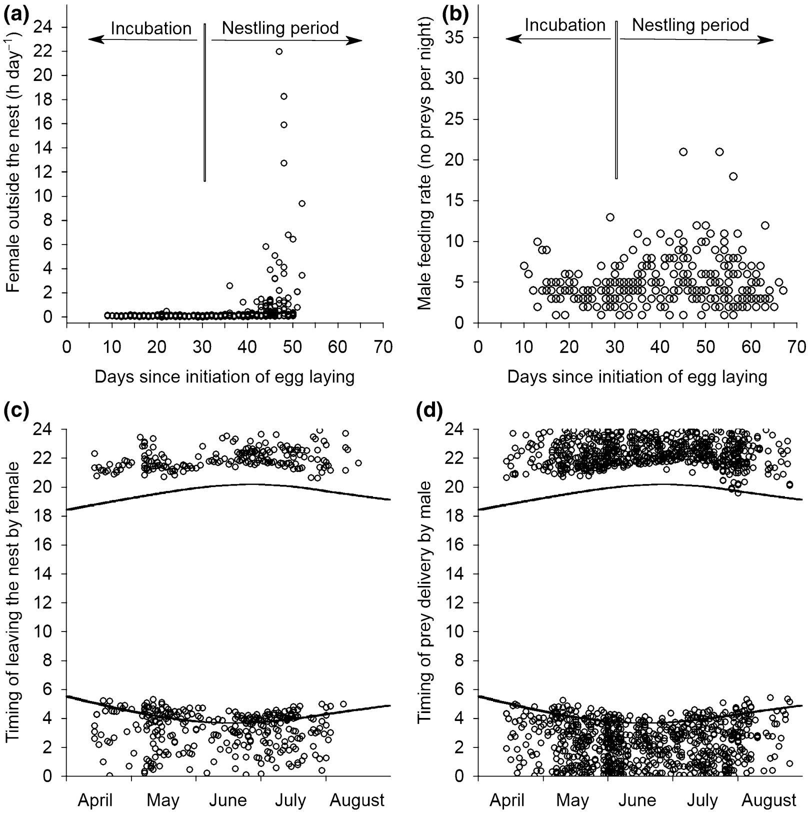

Fig. 5. Female and male Tengmalm's owl activities found using the smart nest boxes: (a) time (in hours per a day) spent by owl females outside the nests (N = 8) during the nesting period; (b) male feeding rate, that is the number of prey items delivered by male owls to the nests (N = 8) during the nesting period (note that the period 0–30 days indicates the incubation phase and the period 31–70 days indicates the nestling and fledgling phase); (c) timing of leaving the nest by females during the breeding season (i.e. from April to August); and (d) timing of prey delivery by males during the breeding season. Row data are presented. Timing of sunset and sunrise is fitted by black lines.

memory capacity. We suggest that the sufficient reserves of battery capacity were achieved through the periodic switching of the system between the awake and sleep mode according to sunset and sunrise which varied greatly throughout the breeding season and which determined activity of owls. The lowest power consumption was found during the mid-summer, that is around June 21, when the night length was about 7·5 h, and the highest power consumption was in April and August, when the night length was more than 10 h.

We used a customized event detector characterized by the unique short trigger speed (16 ms) which was fast enough to snap fast moving owls and simultaneously it ignored the

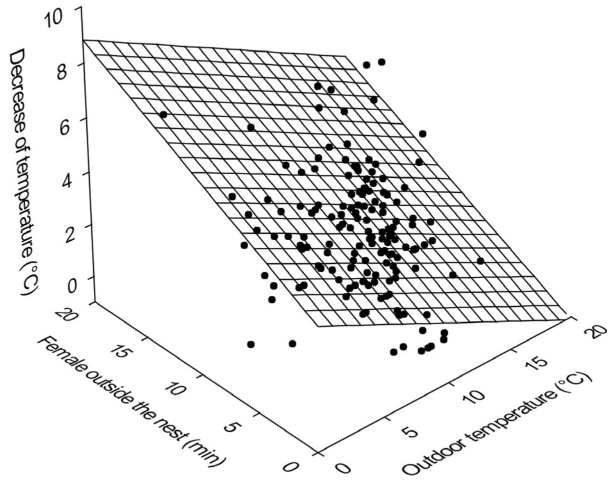

Fig. 6. The temperature decrease in Tengmalm's owl clutches (i.e. difference in temperature of the clutch between female departure from the nest and female entering to the nest, row data are presented) in relation to both outdoor temperature (°C) and time (in min) spent by owl females outside the nests ($N = 5$ clutches).

sunlight and insects (we recorded only one video event without any owl activity). The event detector helped to record only actions of interest, which resulted in 1 GB card capacity used in 1 week. Sufficient reserves of memory card capacity were achieved despite the system using two consecutive cameras – the door camera which recorded the male provisioning in detail, followed by the overview of the activities of the female and the nestlings recorded by the floor camera. A more serious limitation was posed by the size of the temporary storage for individual video frames, which was 110 MB. About 101 MB of this temporary memory was typically used, and thus, it was important to bear this limitation in mind during system configuration. However, all acquired video recordings were of sufficiently high quality, both for the research objectives and for the promotional video. Finally, we appreciate that the time needed for the data download and the battery replacement, including the handling of nestlings, ringing, and identification of stored prey, took only one hour per SNBox, which allowed us to service all four SNBoxes in 1 day.

While RFID technology is commonly used and well accepted in veterinary medicine, animal-farming and animal-tracking (e.g. Voulodimos *et al.* 2010; Catarinucci *et al.* 2014), we applied this technology for recognition of sex of bird parents during nesting in the wild. However, the chip reader device, which was embedded inside the SNBox, worked unreliably. Post-season laboratory experiments showed that the metal cover, the antenna shape, and the movement speed of individual could have significant impact on the RFID reader performance (see Appendix S3 for detailed information). Despite these limitations, we obtained a good overview of the individuals using this method (the RFID code was successfully scanned in 74% of all owl passes). Moreover, the pair of cameras helped us to identify the sex of the owl parents when RFID reader failed. We suggest the chip reader shows a high potential as a simply applicable and cheap tool with low power consumption for identification of individuals living under natural conditions which regularly visit the same place, and its use in other camera systems will depend on the subject being monitored and the research questions in particular.

The temperature and light sensors were the least reliable parts of the system. Post-season analyses showed that the I2C bus connected with the sensors was not resistant to interference. The problem was fixed by detecting bus failures and recovering from the state by bus or system reset.

Finally, we found that male parents showed partial perception of the glow from the IR light source during the first days after camera installation. However, all males adapted to the glow of IR light suggesting the glow did not affect data collection.

BIOLOGICAL INFORMATION

The SNBox allowed us to monitor owl nesting continually during the incubation, nestling and fledgling phases. We identified 12 types of Tengmalm's owl activities in total, three of which were not previously documented. We also produce a video containing unique information on owl nesting. In the light of previous studies (Zárybnická 2009; Zárybnická & Vojar 2013), we confirmed that male Tengmalm's owls deliver most of the prey to the nest, while females incubate the eggs and brood nestlings. Simultaneously, male owls increased their feeding frequency with the nestling age, while the females decreased their time spent in the nest. Both male and female parents shifted timing of their activities according to sunset and sunrise. The period of their activity gradually got narrower from April to late June with shortening the night length, and it again spread after mid-summer with prolonging the night length (see also Zárybnická, Korpimäki & Griesser 2012). As a result, outdoor light intensity at time of owl activities did not differ significantly among months.

For the first time, we observed that males hand over each prey directly to the female or their fledgling, typically from bill to bill. It has previously been documented in other owl species that males hand over the prey to the female's bill during copulation (König & Weick 2008); however, our findings extend this behaviour to the entire nesting period. Another specific activity of parents was observed during fledgling phase, when young were preparing to leave the nest. At this time, both males and females (independent of each other) were seen to deliver prey to the nest, showing it to the fledglings, and then leaving the nest with the prey. Studies of black kites (*Milvus migrans*) and loggerhead shrikes (*Lanius ludovicianus*) demonstrated that parents decreased their feeding rate during the time of fledgling or called to fledglings from afar to entice them out of the nest (Bustamante & Hiraldo 1990; Woods 1993). We speculate that the behaviour observed in Tengmalm's owl parents can be a strategy to lure the young to fledge. Finally, we observed several cases when the female left the nest box with a prey item (four times with shrews and once with a bird), which the male had delivered a few seconds before, and she returned to the nest with no prey a few minutes later. Newton (1979) mentioned that the prey that is unfinished at one meal may be stored by the parent away from the nest and brought back to the nest on another occasion. Because both shrews and birds represent an alternative prey of Tengmalm's owls (Zárybnická, Riegert & Šťastný 2013), one explanation for this behaviour could be to take a non-preferred prey away from the nest. However, we cannot exclude the possibility that female owls fly out from the nest in this manner to consume the prey themselves, away from their young.

Since the amount and structure of diet in birds of prey may be underestimated using prey-remain collections and pellet analyses, prey identification with camera monitoring may be a more suitable method (Zárybnická, Riegert & Šťastný 2011). Using the SNBoxes, we were able to recognize 98% of all prey items delivered to owl nests as mammals or birds, and to identify 77% of all prey items to family, subfamily, genus or species level. Moreover, this method allowed us to evaluate the number of prey delivered by male and female separately, the frequency of prey decapitation, the proportion of bird adults and nestlings in the diet, as well as the location of the stored prey inside the nest box. In more detailed study, we could also evaluate changes in the structure of the owl diet during the breeding season, time of the night, or the nesting phase.

It was shown that heat losses from the egg to the environment represent an important limitation during the incubation process (Deeming 2002). We found that the temperature decrease inside owl clutches during female absence was on average 3·2°C and increased with both increasing time spent by the female outside the nest and decreasing outdoor temperature. As a result, female parents reduced the time spent away from the nest with decreasing outdoor temperature, suggesting that the heat losses from the clutch are a limiting factor for Tengmalm's owl.

USING SMART NEST BOXES FOR OTHER ANIMAL SPECIES

The SNBox can be easily adjusted for research on other animal species. Specifically, one could simply change the user system configuration by adjusting the awake/sleep time, depending on activity pattern of monitored species. Moreover, modifications to the software would allow a deep system adjustment and replacing the individual hardware components would enable the system to monitor many different tasks. As a result, the system could be used for both diurnal and nocturnal animals breeding in nest boxes or bigger cavities, as well as for research on other animals in which the action of interest is triggered by actively crossing a specific spot. We believe the system can be applied to birds, mammals or reptiles using nest boxes to breed, roost, hibernate, or store food so as to monitor their activities and circadian rhythms, feeding ecology, parental care or sibling competition. Additionally, the modification of sensitivity of the event detector would allow monitoring of insects using cavities and nest boxes. The most expensive part of the system for monitoring the Tengmalm's owl nests was the pair of industrial cameras, which were necessary to collect the required data and which allowed high-quality video recordings. We suggest the use of cheaper cameras could reduce the system cost to two-thirds of the actual price (€1000). Moreover, further development of the system could allow significant improvements, including audio recording, Wi-Fi connectivity, online video transmission and self-acting setting of the awake/sleep time of the system depending on the outdoor light intensity. We believe this monitoring system will provide unique insights into the lives of cavity-dwelling animals, as we show by results of the present study on Tengmalm's owl.

Acknowledgements

We would like to thank anonymous reviewers and Jan Riegert for valuable comments on the manuscript. This study was supported by the Czech University of Life Sciences Prague (CIGA grant No. 20164202) and by the Center for Applied Cybernetics (TACR grant No. 01020197).

Data accessibility

Data for the statistical analyses can be found at Dryad entry doi:10.5061/dryad.c89g9 (Zárybnická *et al.* 2015b).

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Received 26 August 2015; accepted 4 November 2015
Handling Editor: Diana Fisher

Supporting Information

Additional Supporting Information may be found in the online version of this article.

Figure S1. Architecture of the embedded system in the smart nest box (SNBox).

Appendix S1. Examples of animals using artificial boxes.

Appendix S2. Hardware and software design of the SNBox.

Appendix S3. Post seasonal laboratory experiment on reasons for the failure of the chip reader.

Video S1. An original video containing unique biological information on Tengmalm's owl nesting.

Video S2. An original video records showing partial perception of male Tengmalm's owl to the glow from the IR light during the first days after camera installation (notice that the male leaves the nest opening without delivering the prey to the females, perhaps out of fear).

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J. Šindelář, P. Kubizňák, and M. Zárybnická (2015). “Sequential polyandry in female tengmalm’s owl (Aegolius funereus) during a poor rodent year”. In: *Folia Zoologica* 64.2, pp. 123–128. ISSN: 01397893

Folia Zool. – 64 (2): 123–128 (2015)

Sequential polyandry in female Tengmalm's owl (*Aegolius funereus*) during a poor rodent year

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Received 19 February 2015; Accepted 20 July 2015

Abstract. In birds of prey, food availability affects the entire breeding process, including reproductive success. Sequential polyandry, sometimes documented in raptors and owls, has been observed occasionally in Tengmalm's owl in years of high food availability. In this study, the effect of food supply on the reproductive strategy of the central European Tengmalm's owl population has been investigated. The availability of the main prey of owls was significantly below average in the study year 2014. This resulted in low breeding density of owls, delayed egg laying, small clutch sizes, and low reproductive success. Nevertheless, successful sequential polyandry of one Tengmalm's owl female was recorded during the breeding season. The polyandrous female laid four eggs in each nests, and 50 % and 75 % of four hatched nestlings left the nest during the first and second breeding, respectively. In both nesting attempts, the two-year old female was of a substandard body mass and she abandoned the fledglings before they left the nests. Prey delivered by males to both nests was comprised mainly of alternative prey (birds and shrews). The results of this study suggest that there are probably some other factors, in addition to food availability, that may play a role in Tengmalm's owl's decisions in matters of parental care.

Key words: boreal owl, polygamy, reproductive success, food abundance, sex ratio, diet structure

Introduction

Multiple breeding in one season is a well-known strategy, especially in songbirds (Clutton-Brock 1991, Reynolds & Székely 1997). Regular social polygyny, where the male partially or entirely deserts his offspring and re-mates in early or sometimes later phases of the breeding cycle is quite common; it occurs in at least 10 % of bird species from at least ten orders (review by Bennett & Owens 2002). Social polyandry, on the other hand, is a type of polygamy where the female deserts her offspring and re-nests in the same breeding season; it is less common among birds, often associated with uniparental care and sex-role reversal (Oring 1986, Owens 2002). Choosing this reproductive strategy results in higher nestling production, but forces the female to abandon the nestlings from each nest earlier, which is reflected in a reduced survival rate in the late nestling and post-fledging stages (Oring 1986, Székely 1996, Eldegard & Sonerud 2009).

Social polyandry is used in only 1 % (Oring 1986), respectively less than 5 % of all bird species (Bennett & Owens 2002) and mostly occurs in precocial species of birds (it is most common in waders; e.g. Amirault et al. 2004, Kosztolanyi et al. 2006). Chicks of precocial species are capable of feeding themselves, so females can choose to desert their broods after clutch completion and leave offspring nurturing to their mates (Oring et al. 1983, Andersson 2005). However, multi-nest sequential polyandry in birds with altricial chicks, where males are either unwilling or physiologically unable to perform the majority of incubation, is sometimes also documented (e.g. lesser spotted woodpecker *Dendrocopos minor*, Wiktander et al. 2000; northern flicker *Colaptes auratus*, Wiebe 2005; barn owl *Tyto alba*, Henry et al. 2013).

In raptors and owls, in which reversed sexual dimorphism is evolved and both sexes have usually distinctly divided parental roles (e.g. Zárybnická & Vojar 2013), polyandry is occasionally observed when food is abundant (Beissinger & Snyder 1987, Carlsson et al. 1987, Korpimäki et al. 2011). In the northern European population of Tengmalm's owl (*Aegolius funereus*) 12 re-mating females from a total of 1135 females were found in years of high vole spring abundance (Korpimäki et al. 2011). Furthermore, Eldegard & Sonerud (2009) revealed that the nest desertion frequency of female Tengmalm's owls increased with both prey availability and an increase the body reserves of parents (especially of the male).

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Similarly, in a central European population, the frequency of female offspring desertion occurred more often in years of high food availability and two cases of female re-mating were documented when food was abundant (Zárybnická 2009a). However, there are still only rare examples of female desertion and female re-mating in same season, as well as there is little information regarding the environments in which females are able to re-mate and how the individual nestings of re-nesting females differ from each other (Hipkiss & Hörnfeldt 2004, Korpimäki et al. 2011).

Food abundance is an important factor driving the entire breeding process of Tengmalm's owl, in particular it affects breeding density, laying date, clutch size, reproductive success, and diet structure (Korpimäki & Hakkarainen 2012). In this study, we investigate the effect of food availability on the reproductive strategy of Tengmalm's owls in areas of the Ore Mountains (Krušné hory), Czech Republic, in 2014. We predict that (i) in a year with poor prey availability there will be a low breeding density of Tengmalm's owl nests, owl females will lay small clutches, few fledglings will leave the nests, the timing of nesting will be delayed, and the prey structure will comprise of a high proportion of alternative prey species (i.e. birds and shrews). In contrast, in a year with high prey availability there will be a high breeding density, the owls will raise more fledglings and their diet will be comprised mainly of voles and mice. Simultaneously, we predict that (ii) in a year with poor prey availability, there will be no record of sequential polyandry and, if present, it would only be so as a result of unsuccessful nesting in the first place. Conversely, in a year of rich prey availability sequential polyandry will be more frequent.

Material and Methods

Study area

The study was conducted in the northern part of the Czech Republic (N 50°, E 13°), close to the border with Saxony, in 2014. The study area is situated in forests damaged by industrial air pollution, on plateaus of the Ore Mountains (735-956 m a.s.l.). The habitat at this study site is covered with spruce forest fragments, open areas, and forest clearings (dominated by wood reed *Calamagrostis villosa*), solitary trees (mostly European beech *Fagus sylvatica*) and secondary growth of young trees, mainly blue spruce *Picea pungens*. In this habitat, Tengmalm's owl primarily breeds in nest-boxes (> 90 % nests) as natural cavities can only be found in rare solitary beech trees. Within these habitats, during 1999-2013, the number of deployed nest-boxes varied yearly between 100 and 167 (126.6 ± 26.8). In 2014, 212 nest-boxes for Tengmalm's owl were placed in an area covering 110 km^2. The boxes were evenly distributed within the study area and were usually placed at the edge of forest patches.

Field procedures

In 2014, data on breeding density (expressed as the number of nesting attempts per 100 nest-boxes available), clutch size, reproductive success (expressed as the number of fledglings that left the nest) and laying date were collected by regular inspection of nest-boxes. All nest-boxes were inspected from late March to late August at intervals of one to three weeks to detect new breeders. All nests found in 2014 were protected against marten predation by a metal cover. To assess owl breeding production in 2014, the data collected were compared with a long-term data set on Tengmalm's owl nesting in the Ore Mountains covering 2000-2013.

Prey abundance

In 2014, the abundances of small mammals were assessed using snap-trap captures. The captures were carried out in the season twice – at the beginning of June and at the beginning of October. The traps were laid out in three trapping squares of 100 × 100 m; spacing of the traps within each square was 10 m, i.e. a total of 121 traps per square. The traps were in place for three days and checked once a day. Trapping squares were situated in open areas and secondary stands of blue spruce where vegetation is dominated by wood reeds. All captured mammals (31 individuals) were identified to the species level. To assess prey availability in 2014, the collected data were compared with a long-term data set on prey availability in the Ore Mountains during 2000-2013 (1117 individuals). Prey availability for that data set was collected by the same methods as in 2014.

Molecular sexing

For molecular sexing, a 50 µl blood sample was taken from each nestling in 2014, via a brachial vein puncture under the wing, approximately 14 days after hatching, following the methods of Hipkiss & Hörnfeldt (2004). Sex determination of the nestlings relied on polymerase chain reaction (PCR) amplification of one intron from the sex chromosome linked *CHD1* gene, which in birds differs in size between the Z and W chromosomes (Fridolfsoon & Ellegren 1999); males showed only the shorter Z-fragment, while females were characterised by displaying both a 1.2 kb W-specific and a 0.7 kb Z-specific fragment (Fridolfsoon & Ellegren 1999).

Camera monitoring of polyandrous nests

A camera system embedded in a nest-box (consisting of a computer, two cameras with infrared lighting, a chip reader device, an infrared light barrier, and a 60 Ah 12 V traction battery) was used to determine the prey delivered to the polyandrous nests in 2014. Pictures taken by the nest-box camera system enabled the determination of the presence of individual parents (i.e. male and female) in the nest, and the identification of prey delivered by owl parents as mammals (to the genus or species level) or birds. Only 2.3 % (n = 7 items) of all delivered prey were not determined. Each polyandrous nest was recorded over a mean period of 37.5 ± 20.5 days.

Statistical analyses

Results are reported as mean ± standard deviation. The taxonomic composition of the diet structure between nests was compared using χ^2 tests. All data analyses were processed in the Statistica 6.0 software package (StatSoft Inc. 2010).

Results

Prey availability

In 2014, both spring and autumn prey availability was lower than the long-term yearly mean (1999-2013) and, except for pygmy shrew *Sorex minutus*, none of the prey species reached their 14-year mean abundance (Table 1). Simultaneously, the availability of most small mammal species in 2014 increased from spring to autumn (Table 1).

Basic breeding data

In 2014, there were 10 nesting attempts of Tengmalm's owls and the breeding density was 4.7 nesting attempts per 100 nest-boxes available. Females started egg laying on 13th May ± 31 days. Eight of the nesting attempts were successfully completed and two were deserted by the female before any of the eggs hatched. In successful nests, 3.6 ± 0.5 eggs per clutch were laid and 2.1 ± 1.1 young per nest fledged. The sex ratio of the fledglings in 2014 was female-biased, at 57.3 ± 39.7 %. Breeding density, clutch size, and the number of fledglings in 2014 were all lower than their respective long-term yearly means (2000-2013) and the laying date was delayed (Table 2).

Sequential polyandry

In 2014, one of the ten observed females successfully nested twice during the breeding season. The two-year

Table 1. Spring and autumn small mammal availability in the Ore Mountains, the Czech Republic, estimated by June and October snap-trapping and expressed by the numbers of individuals per 100 trap-nights. Data are shown as yearly mean ± SD in period 2000-2013 (n = 14 years), and in 2014 (n = 3 squares) separately.

Taxa	Spring 2000-2013	2014	Autumn 2000-2013	2014
Microtus agrestis	0.47 ± 0.42	0.09 ± 0.16	0.63 ± 0.69	0.28 ± 0.28
Microtus arvalis	0.05 ± 0.13	0	0.08 ± 0.14	0
Microtus subterraneus	0	0	0.01 ± 0.02	0
Myodes glareolus	0.66 ± 1.10	0	1.69 ± 2.69	0.37 ± 0.16
Apodemus sylvaticus	0.03 ± 0.10	0	0.03 ± 0.04	0
Apodemus flavicollis	1.16 ± 1.74	0.28 ± 0.48	0.94 ± 1.13	0.46 ± 0.80
Sorex araneus	0.21 ± 0.17	0	0.87 ± 1.05	1.19 ± 0.32
Sorex minutus	0.02 ± 0.05	0.09 ± 0.16	0.24 ± 0.53	0.09 ± 0.16
Total	2.45 ± 2.89	0.46 ± 0.42	4.48 ± 4.15	2.39 ± 0.80

Table 2. Data on breeding density, laying date, clutch size and the number of Tengmalm's owl fledglings in the Ore Mountains in the Czech Republic. Data are shown as a yearly mean ± SD in period 2000-2013 (n = 14 years), and in 2014 separately. The breeding density is shown as the number of nesting attempts per 100 nest-boxes available.

	2000-2013	2014
Breeding density	13.3 ± 4.8	4.7 (n = 1 year)
Laying date	April 18 ± 13.4 days	May 13 ± 30.8 days (n = 10 nests)
Clutch size	4.9 ± 1.0	3.6 ± 0.5 (n = 8 nests)
Number of fledglings	3.5 ± 1.4	2.1 ± 1.1 (n = 8 nests)

Table 3. Diet composition of Tengmalm's owls delivered to two sequential nests in the Ore Mountains, the Czech Republic, in 2014.

	First nest		Second nest	
Taxa	Number of prey items	%	Number of prey items	%
Apodemus sp.	4	1.5	2	4.7
Microtus sp. and *Myodes glareolus*	63	23.8	13	30.2
Muscardinus avellanarius	1	0.4	0	0.0
Sorex araneus	68	25.7	16	37.2
Sorex minutus	7	2.6	5	11.6
Aves	117	44.1	5	11.6
Unidentified prey	5	1.9	2	4.7
Total	265	100	43	100

old female first nested with a similarly aged male and subsequently nested with a male which was more than three years old. The first egg laying of this female fell on 28th March and the second was on 11th June 2014. The nests were 3.02 km from each other. In the first nesting attempt, the female laid four eggs, all nestlings hatched and only two female-fledglings (i.e. 0 % male sex ratio) left the nest. The female abandoned the first nest when two nestlings were present and the eldest was 22 days old; after this point she did not visit the first nest. The female started egg laying in the second nest 23 days after leaving the first one, with a different male. In the second nest, the female also laid four eggs, all nestlings hatched and three fledglings (two male fledglings and one female fledgling, i.e. 67 % male sex ratio) left the nest. The female abandoned the second nest when three nestlings were present and at the time when the oldest nestling was 20 days old; after this point she visited the second nest once.

During the first nesting, the female weighed 157 g (measured seven days after laying of the first egg) and the male was 92 g (57 days after laying of the first egg). During the second nesting, the same female weighed 145 g (43 days after laying of the first egg) and her new partner weighed 108 g (57 days after laying of the first egg). During the first nesting period, the male delivered 265 prey items within 52 days and during the second nesting the other male delivered 43 prey items within 13 days. There were differences in the taxonomic composition of the diet structure between the first and second nesting ($\chi^2 = 37.2$, df = 6, $P < 0.001$). In the first nesting, bird prey was the dominant diet component (44.1 %); within this, there was a high proportion of songbird nestlings present (44.0 % of all birds collected, in all stages of development). Apart from birds, the most frequent preys were shrews (28.3 %), and voles (23.8 %). In the second nesting, the most common prey components were shrews (48.8 %, mainly common shrew) and voles (30.2 %), while birds only comprised 11.6 % of diet (no bird nestling was present, Table 3).

Discussion

Vole populations tend to be relatively more stable both within and between years in central Europe, compared to northern Europe, where they undergo regular 3-4 year cycles and large multi-annual and intra-seasonal changes in abundance (Hansson & Henttonen 1985, Hanski et al. 1991), which can result in increased nestling mortality and poor reproductive success of northern owl populations (Zárybnická et al. 2015). In this study, a significant effect of food shortage in our central European study site on the breeding processes of Tengmalm's owls has been found. In particular, there was a very low availability of both of the main prey (mice and voles) during spring in the Ore Mountains in 2014; this resulted in low owl breeding density, small clutches, and low reproductive success of owls, expressed as the number of fledglings. All these breeding parameters were significantly lower than their long-term averages. Also a delay of 25 days was found in the mean egg-laying date, in comparison with the 14-year average. Avian predators, and Tengmalm's owl in particular are well known for their ability to adjust their reproductive strategies across space and time, according to the actual food availability (e.g. Hakkarainen et al. 2003, Byholm et al. 2007) and the results presented in this study are in accordance with this (our first prediction).

In contrast to our second prediction, a case of sequential polyandry has been recorded, where a female successfully completed both clutches and broods, and 50 % and 75 % of her fledglings, respectively, left the nests. In both nesting attempts, the female deserted the nests before the fledglings had left the nest, leaving them to be cared for by her mates. The mean body mass of Tengmalm's owl females during the first half of the incubation period reached 181 ± 12.5 g, and during the first half of nestling period 168 ± 16.8 g (Korpimäki 1990). Although the polyandrous female was two years old, which could give her advantage for reproductive success (Korpimäki 1988b), she was at a substandard body mass during both nesting attempts (157 g during the first half of incubation period and 145 g during the first half of nestling period, respectively). Due to both the food shortage in the study season and the female's substandard body mass, sequential polyandry was unexpected.

The diet of the owls was composed mostly of alternative prey (birds and shrews were dominant in both nesting attempts; 72.4 % and 60.4 %, respectively, however, the male in the first nesting attempt did provide a higher proportion of birds (44 %) than its successor in the second nest. It has been shown that Tengmalm's owl is a generalist and its prey structure varies depending on prey availability across time and space (Korpimäki 1988a, Hakkarainen et al. 2003, Zárybnická 2009b, Zárybnická et al. 2013). In northern areas of Europe, voles of the genera *Microtus* and *Myodes* form a large part of Tengmalm's owl diet (Korpimäki 1988a, Korpimäki & Hakkarainen 2012), while both voles and mice (genus *Apodemus*) are important prey of owls in central Europe (Zárybnická et al. 2011, 2013). Nevertheless, there is evidence that in both areas, the owls shift to alternative prey (small birds and shrews) during low vole abundance (Korpimäki 1988a, Zárybnická et al. 2013). Korpimäki (1981) highlighted an increase of birds present in the owl's diet from April to June, which is not consistent with our findings. We suggest that the increasing availability of voles and mice in our study area during the course of the season (from spring to autumn 2014), and the different habitat quality of the nesting territories (Norway spruce *Picea abies* forest dominated in first nesting territory, while open areas with secondary stands of blue spruce and European larch *Larix decidua* dominated in the second one) could have resulted in the different prey structure delivered by the individual males to their nests. Moreover, the decreasing availability of songbird nests from spring to late summer could influence the present of bird nestlings in the owl's diet.

Fledglings leaving the first polyandrous nest were female biased (100 %), while fledglings leaving the second nest were male biased (67 %). Since the sex ratio of Tengmalm's owl nestlings do not differ between hatching and fledgling (Hörnfeldt et al. 2000), we can assume the similar sex ratio was present in the hatched nestlings (i.e. brood sex ratio). The sex ratios of broods produced by individual females are not well known (Hipkiss & Hörnfeldt 2004) and thus this study provides valuable findings, indicating that the brood and fledgling sex ratios can differ in sequentially polyandrous females within a season. Moreover, the male breeding with the female in the second nest was older (more than three years old) than the male in the first nest, and in line with this, it also had a higher body mass. Studies have proven that older Tengmalm's owl males produce more fledglings than younger males (Korpimäki 1988b, Laaksonen et al. 2002), which is consistent with our findings.

In conclusion, this study confirms that Tengmalm's owls adjust their reproductive strategies in terms of laying date, breeding density, clutch size, and reproductive success to prey availability. Simultaneously, the study has documented one case of successful sequential polyandry in a year of food scarcity. The two-year-old female with substandard body mass laid four eggs in each clutch, but the number of fledglings and sex ratio of fledglings differed in each nesting attempt. This suggests that not only can food availability drive an owl's decision about parental care, but other factors probably play a role as well.

Acknowledgements

We are grateful to V. Bejček, F. Sedláček, K. Šťastný, and J. Zima for their assistance in determining small-mammal abundance in the field. This study was supported by the Czech University of Life Sciences Prague (CIGA Grant No. 20144203).

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P. Kubizňák et al. (2019). "Designing network-connected systems for ecological research and education". In: *Ecosphere* 10.6. ISSN: 21508925. DOI: `10.1002/ecs2.2761`

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EMERGING TECHNOLOGIES

Designing network-connected systems for ecological research and education

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Citation: Kubizňák, P., W. M. Hochachka, V. Osoba, T. Kotek, J. Kuchař, V. Klapetek, K. Hradcová, J. Růžička, and M. Zárybnická. 2019. Designing network-connected systems for ecological research and education. Ecosphere 10(6):e02761. 10.1002/ecs2.2761

Abstract. While networked sensors are becoming a ubiquitous part of many human lives, their applications to the study of wild animals have been largely limited to off-the-shelf and stand-alone technologies such as web cameras. However, purpose-designed systems, applying features found in Internet-of-Things devices, enable more efficient gathering, managing, and disseminating of a diverse array of data needed to study the life histories of wild animals. We illustrate these claims based on our development of a system of networked nest boxes that we created to study nesting birds in urban environments. This system uses general-purpose processors within nest boxes to perform edge computing to control data acquisition, processing, and management from multiple sensors. A central data-management system permits easy access to all data, once downloaded, which has facilitated our uses to date of this system for formal university- and school-level education, and informal science education.

Key words: ancillary sensors; animal behavior; bird nesting; birdsonline.cz; camera monitoring; edge computing; formal and informal education; Internet of Things; live video stream; smart nest box; urban ecology; video capturing.

Received 8 January 2019; accepted 11 April 2019; final version received 3 May 2019. Corresponding Editor: Fei Fang.

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INTRODUCTION

There is a long history in ecological research of collecting observations of animals indirectly, using cameras, sound recording devices, and other forms of data loggers. Such devices have allowed the collection of information in situations in which direct human observation would require too much time, money, and field effort, or even change the natural behaviors of the observed animals (Cutler and Swann 1999, Reif and Tornberg 2006, Cox et al. 2012). However, applications of similar technologies in human society, with the Internet of Things, point to the potential for much more sophisticated collection of ecological data. Most obviously, connection to the Internet allows automated downloading of data as well as remote monitoring and control of devices (Madhvaraj and Manjaiah 2017). As another example, more sophisticated edge computing—providing substantial computational resources at the data loggers—can enable the integration of multiple streams of data at their source, facilitating subsequent data management. In order to achieve the full benefits of this sophistication, researchers need to design entire systems for data collection that are tailored to specific needs, rather than constraining the data that they collect based on the availability of off-the-shelf devices (Cox et al. 2012, Trolliet et al. 2014) simply because they are readily available at low cost.

The study of reproduction of many animal species, particularly animals such as cavity-nesting birds, lends itself well to the use of integrated monitoring systems in order to collect information on aspects of nesting biology. Cavity-nesting birds have been used as model systems for decades in order to study an array of questions in population and behavioral ecology. Examples of research topics include diet structure and foraging effort, nest attentiveness, and parental cooperation and competition; sibling competition and survival rate in relation to varying weather (e.g., temperature, precipitation, humidity, and air pressure; Charmantier et al. 2008, Irons et al. 2017); and responses to anthropogenic changes in environments (e.g., light, noise, and air pollution; Dominoni et al. 2014, Shannon et al. 2016).

The automated collection of data from cavity-nesting birds not only facilitates research but can additionally expand access of the general public to the life sciences, at the time of increasing urbanization and disconnection of people from the natural world (Balmford et al. 2002). Scientists can share research data and results with the public through the Internet in real time, allowing the public to be involved in the research at levels varying from sharing images of natural systems through to crowdsourcing of data collection and processing in a citizen science project. The most basic application is the dissemination of live streaming and video capturing of bird activities in their nests via social media (Zárybnická et al. 2017). Availability of such video creates the potential for educational activities such as direct observation of animal life on screens placed in schools that can supplement generic textbook information with real-life bird observation. For this potential to be realized, however, the infrastructure for transmitting, storing, and displaying information needs to be built in a way that allows for broad dissemination of the information being collected by camera and sensor systems.

Here, we describe the lessons that we have learned from designing, building, and deploying nest monitoring systems that we created for both research and educational purposes and that allow (1) live video streaming and video capture of cavity-dwelling animals over the course of an entire year; (2) the collection of measurements of local weather and environmental data including temperature, light intensity, humidity, and air pressure; (3) automated downloading, storage, and dissemination of video and audio data; (4) automated processing of all streams of data; (5) remote monitoring and configuration of the system; and all while (6) retaining the potential to extend the system's functionality in the future. We discuss the major design decisions that we made in developing our system including evaluating the strengths and limitations of our current system, offer suggestions regarding the trade-offs involved in designing any such system, and note ideas for future development and applications in scientific and educational fields.

MATERIALS AND METHODS

Here, we first describe the criteria that we set for the design of our system for automated nest box monitoring, and then describe the systems themselves, both model 2.0 and 3.0 SNBox camera systems, and related networking infrastructure.

Since we aimed to build the modular camera system whose functionality could be extended in the future with minimal technological limitations, we developed the entire camera system from the ground up, including hardware and software technology, and only the cameras were standard commercial products. Our main design criteria for new system were as follows:

Hardware criteria:

1. Flexibility to collect a wide range of environmental data, and the flexibility to incorporate new features into the basic design.
2. Small dimensions of all technical components to be suitable for embedding in the structure of the nest box.
3. High reliability and long-term life span of all technical components, including the housing for all devices such that the system would work reliably during extreme weather conditions, and be easy to install.
4. Energy efficiency.

Software criteria:

1. Reliable continuous operation.
2. Minimum video trigger delay.
3. Automated data delivery and management, reducing potential errors associated with manual steps in the data-management workflow.
4. The ability for real-time and retrospective viewing of any data both by researchers, and for educational purposes by the general public.

Financial criteria:

1. Lower need for on-site maintenance, thus substantially reducing the cost of labor for maintenance that could limit the number of units that can be deployed at one time.
2. Reliability and professional design that would allow the potential for commercial production of the system.

Background

We have designed and deployed three generations of a modular camera surveillance system for monitoring of cavity-dwelling animals, particularly birds. We designed the first camera system (model 1.0) to monitor boreal owl (*Aegolius funereus*) nests located in forest areas. We completed this system in 2014, and it consisted of a pair of industrial cameras with IR lighting, an IR light activity detector, an RFID reader, and temperature and light intensity sensors. This system was powered by a battery. Data were downloaded manually via a cable: Our initial design did not feature automated data transfer capabilities due to non-availability of Internet connections in forest areas. We embedded this camera system in a wooden bird box forming a so-called smart nest box (SNBox), which is described in Zárybnická et al. (2016).

Here, we introduce two successor SNBoxes (the model 2.0 and model 3.0) that we adapted for monitoring diurnal cavity-dwelling passerine birds inhabiting urban areas where wired Internet connection and mains power are easily accessed. We extended the camera system of both models (model 2.0 and model 3.0) with remote data acquisition and live streaming of animal activities, creating a maintenance-free camera surveillance system whose data could be universally accessible. In particular, we replaced battery powering and regular manual data downloading with full-time powering via standard household electrical connection and automatic daily data transfers from each SNBox to our university server (located at the Czech University of Life Science Prague). In the spring of 2016, we launched the model 2.0 that we evolved from the model 1.0 by partial hardware redesign and software extension. This model was equipped to enable video capture of animal activities, and live streaming at limited frame rate. Recorded video was available to anyone on our project's websites, and live streaming was provided only to the hosting location. To overcome this limitation, we evolved the model 3.0 that we launched in spring 2018. Both hardware and software of this model were complete redesigns. This model allowed video capturing of animal activities at standard frame rate (i.e., 30 fps) and simultaneous live streaming to the Internet. The model 3.0 system also was equipped with additional environmental sensors, desktop applications for processing of data from environmental sensors, and permanent remote connection for automatic system health monitoring and maintenance. Below, we describe the technical features, including hardware and software technology, and results of the use of both camera systems during 2016–2018. We primarily describe the model 3.0 system, while noting the differences found in model 2.0 systems. In Table 1, we also provide the basic technical description of model 1.0 (Zárybnická et al. 2016) to provide a ready comparison among the three generations of systems.

Smart nest box

While standard nest boxes are designed only to house and protect nesting birds, our nest box structures were additionally designed to physically protect the sensors and computer system and allow for wired power and Internet connections. We modified the original wooden construction of the model 1.0 boxes used to monitor boreal owls (Zárybnická et al. 2016), reducing the box size to be appropriate for cavity-nesting passerines and using the same design for model 2.0 and model 3.0 (Fig. 1). We designed the interior to embed all devices, including the computer

Table 1. Summary on the technical specifications of the computer unit, cameras, videos, and other components and maintenance of the model 1.0, 2.0, and 3.0 SNBox camera systems.

Model of monitoring system	1.0 (Zárybnická et al. 2016)	2.0	3.0
Time of completion	2014	2016	2018
Costs	$1,400	$560	$560
Computer Unit			
Manufacturer	Elnico	Elnico	Elnico
Microprocessor	NXP Vybrid VF6 ARM Cortex A5 500 MHz+ ARM Cortex M4 167 MHz	NXP Vybrid VF6 ARM Cortex A5 500 MHz+ ARM Cortex M4 167 MHz	NXP i.MX6SoloX ARM Cortex A9 800 MHz+ ARM Cortex M4 227 MHz
RAM	256 MB	256 MB	1 GB
NAND FLASH	256 MB†	256 MB	256 MB
MicroSD card	4 GB‡	16 GB‡	16 GB‡
Ethernet	100 Mbit/s	100 Mbit/s	100 Mbit/s
WiFi	802.11 b/g/n	No	No‡
Housing	171 × 121 × 55 mm, IP65	125 × 115 × 58 mm, IP53	125 × 115 × 58 mm, IP53
Powering	12 V traction battery	15 V PoE (Power over Ethernet)‡	15 V PoE (Power over Ethernet)‡
Other Components			
Manufacturer	Elnico	Elnico	Elnico
Microphone	Stand-alone	Stand-alone	On-camera
Activity detector	Infrared light barrier	Infrared light barrier	Infrared light barrier
RFID reader	Yes	No‡	No
Light intensity sensor	Photoresistor + ADC	Photoresistor + ADC	Luxmeter
Interior temperature sensor	Yes	Yes	Yes†
Exterior temperature sensor	Yes	Yes	Yes
Hygrometer	No	No	Yes
Barometer	No	No	Yes
Magnetic sensor	No	No	Yes†
External speaker	No	No	Yes†
Extension slots	No	No	Yes†
USB connectors	No	No	Yes†
Camera			
Manufacturer	Imaging Development Systems	Ailipu Technology	Ailipu Technology
Model	UI-1541LE-M	ELP-USB100W05MT-RL36	ELP-USB100W04H-RL36
Resolution	1280 × 1024 px (1.3 MPx)	1280 × 720 px (1 MPx)	1280 × 720 px (1 MPx)
Color mode	Monochromatic	Color (day)/ Monochromatic (night)	Color (day)/ Monochromatic (night)
IR lighting	Always	On low illumination	On low illumination
Connection	USB	USB	USB
Number	2	1‡	1‡
Video			
Codec	MJPEG	MJPEG	H.264
Container	mkv	mkv	mp4
Frame rate	10 fps	6 fps	30 fps
Trigger delay	16 ms	20–200 ms	−3000 to −2000 ms
Video capturing	Yes	Yes	Yes
Live streaming	No	Local network only, dedicated player	Internet, standard stream (RTSP)
Capturing vs. streaming	Capturing only	Mutually exclusive	Simultaneous operation
Maintenance and data handling			
Regular maintenance	Yes	No	No
Remote access	No	Yes	Yes
Remote data acquisition	No	Yes	Yes
Automatic data backup	No	Yes	Yes
Web-published data	No	Yes	Yes

Notes: Costs (in US dollars) and manufacturers are also shown. Please note that all components are custom designed and produced in cooperation with the Elnico company, and only cameras are standard commercial products.

†Property not used or not implemented yet.

‡Value applied in the field. Property is adjustable.

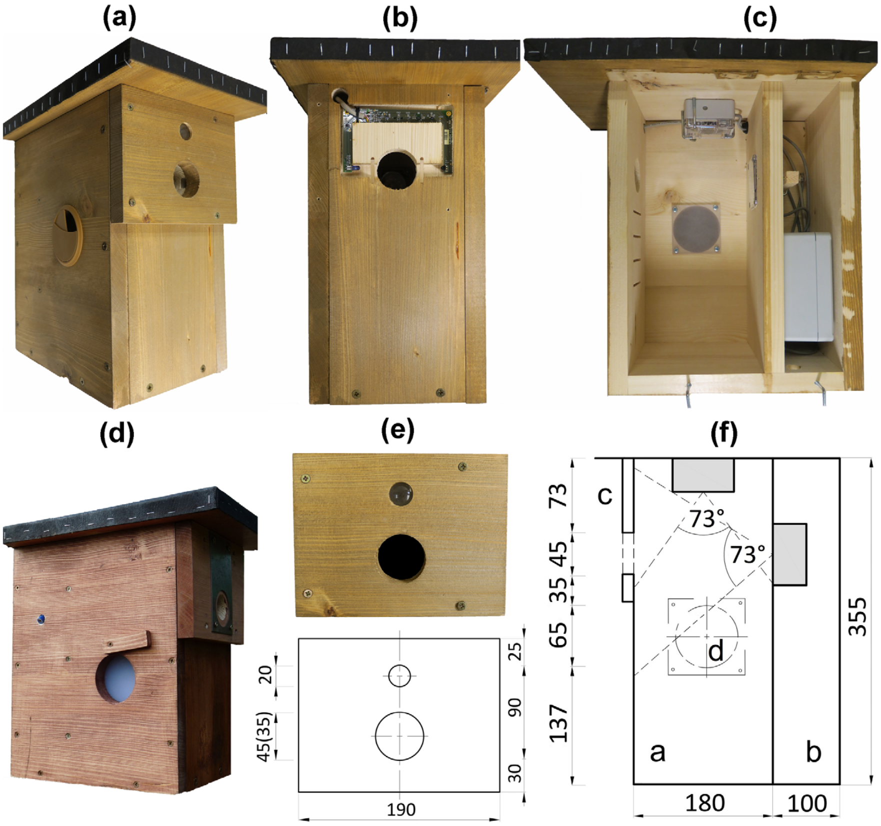

Fig. 1. The design of the model 3.0 smart nest box (SNBox) and its individual parts. (a) The completed SNBox. (b) A front view of the SNBox exposing the IR light activity detector board upon which environmental sensors were also located. (c) The inner SNBox space containing a nesting area with one or two cameras and the electronics area with a computer unit and cabling. (d) Side view of the SNBox with uncovered window and exterior light and temperature sensor (model 2.0 only). (e) Photograph and schematic of the front wooden cover with the entrance (35 or 45 mm) and the lens used to direct light to the illumination sensor. (f) Schematic of the box and its individual parts: a, the nesting area; b, the electronic area; c, the front wooden cover; and d, the window shielded by translucent plexiglass and covered by a removable cover. Outer dimensions are in millimeters. Note that the model 2.0 box only differed in the front wooden cover that did not include the lens, and environmental sensors were located on outside wall instead of being on the IR light activity detector board (e).

unit (Fig. 1c), an IR light activity detector (Fig. 1b), environmental sensors (Fig. 1b, d), and cameras with IR lighting (Fig. 1c). We provided the box with a 45-mm entrance and a groove for placement of the IR light activity detector that was protected from the box exterior with a wooden plank (Fig. 1a, e). The sizes of birds using the boxes could be varied by changing the size of entrance hole in a wooden plank placed over the entrance hole in the main box; we produced planks with 35- or 45-mm entrance for nesting smaller (e.g., Eurasian blue tit *Cyanistes caeruleus*) or larger (e.g., great tit *Parus major* or European starling *Sturnus vulgaris*) bird species, respectively (Fig. 1e). We also equipped each box with a window shielded by translucent plexiglass (Fig. 1d) to provide greater natural illumination inside the box and enable the recording of color video during daylight hours. This window was covered by a removable plastic or wooden cover to manually regulate light intensity inside the box. The overall dimensions of these SNBoxes were up to 355 × 280 × 185 mm, and the weight was 6.2 kg when all components were installed.

Computer unit

To fulfill our criteria for data collection and processing, we decided to build a custom-designed computer unit instead of using an off-the-shelf single-board computer (for comparison with Raspberry Pi, see *Discussion*). We designed and developed the computer unit as the core of the system, connecting to and controlling all peripheral devices, including scheduling, animal detection, data collection, storing and submission, live streaming, and VPN connection and communication. The model 3.0 computer unit (Fig. 2a) was built based on the SQM4-SX6 processor module (Elnico, Dvůr Králové nad Labem, Czech Republic) featuring a heterogeneous dual-core ARM Cortex processor 800 + 227 MHz, 1 GB operating memory, 256 MB permanent storage, and integrated Ethernet circuit. The computer unit was also equipped with a 16-GB microSD memory card (local data storage), 4 universal extension slots, 2 Type A USB connectors, a 3.5-mm audio jack for external microphone, an RJ45 connector for the Ethernet cable connection, and a set of RJ12 female connectors for connecting the peripheral devices. We found RJ12 connectors ideal, offering sufficient number of pins to transmit required power and data (i.e., 6 pins, 2 for power and 4 for data signals), providing a mechanical lock for reliable connection, allowing quick and easy toolless connection and disconnection, and being inexpensive. The model 2.0 computer unit (Fig. 2d) differed primarily in the processor module SQM4-VF6 (Elnico), with heterogeneous dual-core processor 500 + 167 MHz and 256 MB operating memory. This earlier computer unit did not have extension slots or USB connectors.

The system was controlled by a dual-core processor, using Linux and FreeRTOS operating systems running in parallel. This approach combined the advantages of a feature-rich operating system together with minimum latencies and full control of a real-time operating system. In other words, use of FreeRTOS was not inevitable, but it simplified implementation of some device-driver software components and left more options for the future development. FreeRTOS was mainly used to implement non-standard drivers of the IR light activity detector and environmental sensors, which would be more complicated to do under Linux. Most of the application software components ran under Linux, with custom control software, a virtual private network (VPN) client, a Secure Shell (SSH) server, and a Simple Network Management Protocol (SNMP) server. When a signal was received from the activity detector, our application based on the gstreamer library (powerful library supporting all media-handling operations; for details, see https://gstreamer.freedesktop.org) started recording from the cameras, saving the MP4 video with metadata to the local data storage. A gstreamer-based Real-Time Streaming Protocol (RTSP) server was used to publish the live stream over the LAN and VPN and further via a WAN through the university server (for details, see *VPN tunnel*). The software was further responsible for periodic acquisition of environmental data and regular submission of all recorded data to the server-side storage. The model 2.0 software ran under Linux and MQX operating systems, with video recorded in the MKV format, and the live stream was only available over the LAN and required special video player software; no SNMP server was installed.

A single Ethernet cable served as both data and power connection for the unit in order to simplify installation. We used a more expensive foil screened twisted pair Ethernet cable in order to eliminate electromagnetic noise. Data were transmitted through the local network (LAN) to the Internet (WAN). Power over Ethernet (PoE) provided electricity to the unit, requiring a special adapter to inject the electricity into the cable at the host network's end of the cable. We used a PoE-1215-M3 (Sunny Computer Technology Co., Dongguan City, Guangdong Province, China; Fig. 3b), providing up to 12 W at 15 V DC. The computer unit was fitted in a plastic box (115 × 125 × 58 mm), with nine 14-mm holes drilled in a single row. Peripheral cables passed through rubber blank flanges fitted in the holes, in order to achieve ingress protection at the IP53 level. The control unit was installed in the electronics area of the SNBox (Fig. 1c).

IR light activity detector

In order to minimize the amount of video data that needed to be stored, recordings were only

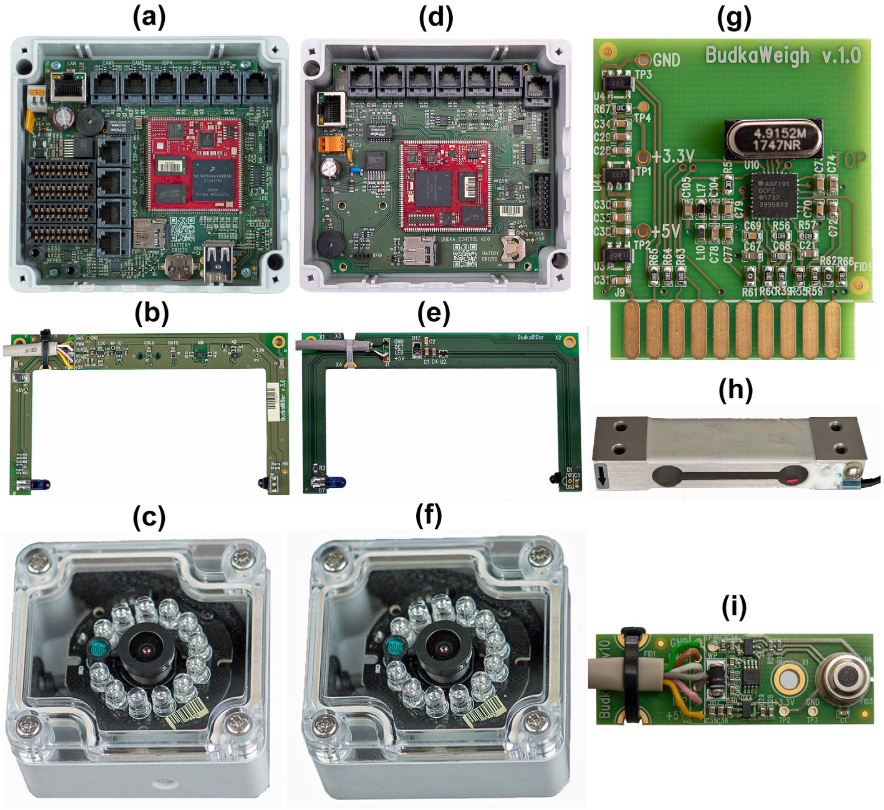

Fig. 2. Electronic components and peripherals of the model 2.0 and 3.0 SNBoxes. The custom-designed computer unit in the opened plastic housing of the models (a) 3.0 and (d) 2.0. The custom-designed IR light activity detector of the models (b) 3.0 and (e) 2.0. The commercial camera of the models (c) 3.0 and (f) 2.0 with a lighting and a custom-designed housing in a box with a transparent lid. Please note that the model 3.0 cameras were equipped with integrated microphones, while the model 2.0 computer unit was fitted with a custom external microphone. (g) An expansion card and (h) a tensometer of the weighing system. (i) IR light contactless thermometer.

collected when an activity sensor was triggered. For both camera models, we used a custom-designed activity detector in the form of an IR light barrier consisting of IR light beam transmitter and a receiver set opposite the transmitter (Fig. 2b, e). To ensure stable mutual position of the transmitter and receiver, we assembled the device on a single U-shaped board and embedded it into the wood of the nest box that surrounded the entrance hole, so that the beam crossed the entrance (Fig. 1b). When the beam was interrupted, the custom driver signaled the Linux control software, which in turn initiated the recording of video.

Environmental sensors

We equipped the model 3.0 SNBox with a range of custom-designed sensors to measure local weather and environmental conditions. We used a thermometer (°C), barometer (hPa), hygrometer (%), and a luxmeter (Lux). We located all these sensors on the IR light activity detector board above the nest box entrance and covered the board with a wooden plank equipped with a clear lens (20 mm diameter) that allowed daylight to reach and be concentrated onto the illumination sensor (Fig. 1a, e). The data from sensors were collected at 30-s intervals and stored in a csv file. The most recent

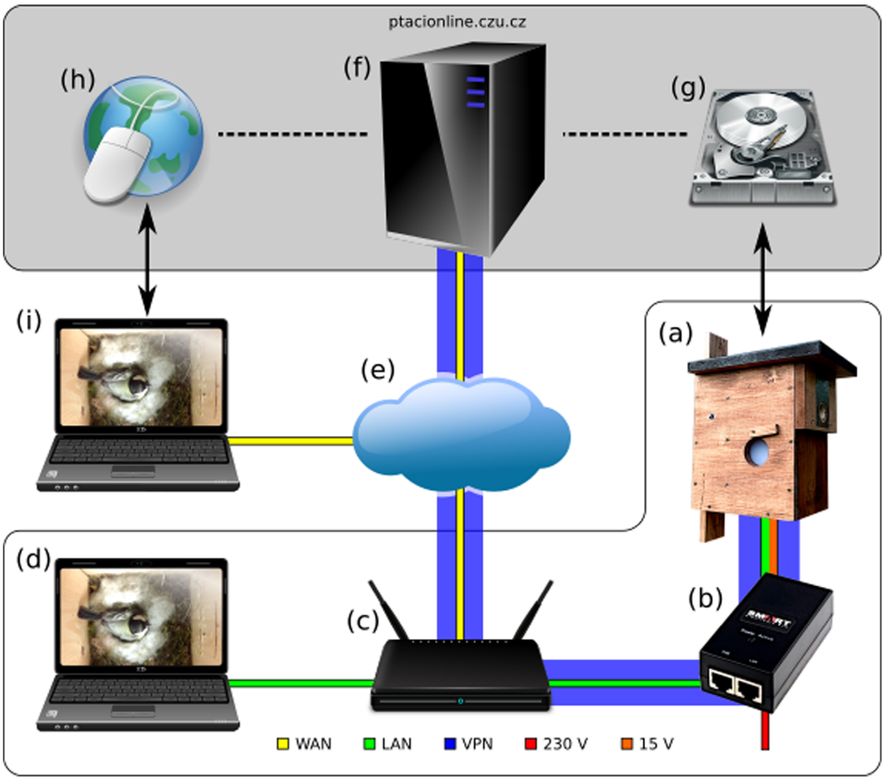

Fig. 3. A schematic of the networking infrastructure of the SNBox camera system (models 2.0 and 3.0). (a) The SNBox installed at the host locality. (b) PoE adapter. (c) Host's router, a central point of the local area network (LAN) and the gate to the wide area network (WAN). (d) Local user PC. (e) The Internet interconnecting all devices together. (f) University server, ptacionline.czu.cz, running all server-side services. (g) Server-side data storage. (h) Webserver, accessible through www.ptacionline.cz and www.birdsonline.cz. (i) Remote user PC.

data were also stored as part of environmental-condition data associated with each activity-triggering event.

The model 2.0 SNBox featured only three sensors. An exterior light-level sensor (yielded dimensionless number from 0 to 4095) and an exterior thermometer (°C) were assembled on one tiny board, housed in a plastic tube, and located on the sidewall of the SNBox (Fig. 1d). An interior thermometer (°C) was assembled on another tiny board, housed in a plastic tube, and placed on the ceiling of the SNBox.

Other sensors

The flexibility provided by our use of a custom-designed computer unit allows for future expansion of the types of sensors that can be deployed. We are developing prototypes for other sensors. One of these prototypes is for a magnetometer, located on the IR light activity detector board, for magnetic field measurement. We are also working on a scale for automatic weighing of the nest content (Fig. 2g, h), an infrared thermometer for contactless measuring of the temperature of the clutch (Fig. 2i), and an external microphone for ambient noise measurements.

Commercial cameras

We strove to find a commercial camera that provided high light sensitivity for operation in dark conditions, operation during nighttime and daytime, sufficiently high video quality (i.e., resolution and frame rate) for comfortable watching on the one hand and limited output file size for saving data storage on the other hand, UVC (USB Video Class) interface, H.264 encoded video stream, low cost, and small size for embedding in the size-limited nest box area. We fitted the model 3.0 with a commercial color CCTV camera (ELP-USB100W04H-RL36; Ailipu Technology, Shenzhen, Guangdong, China) equipped with a sensitive 1280 × 720 px CMOS image sensor, embedded microphone, IR lighting, and an adaptive filter capable of switching automatically between day and night modes according to the scene illumination (Fig. 2c). The camera produces H.264 encoded video at 30 frames per second (fps), which was multiplexed with the audio channel to an MP4 video container. We replaced the original USB connector with the RJ12 male connector and housed the camera in a plastic box with a transparent lid and a small hole for audio tapping (Fig. 2c). The 3.6-mm lens was focused at a distance 170 mm above the wooden bottom of the nest box.

In the previous model 2.0, we had not placed any requirement on the video encoding format. For that reason, the model 2.0 (Fig. 2f) was equipped with different CCTV camera model (ELP-USB100W05MT-RL36; Ailipu Technology). It was very similar to the model 3.0 camera aside from outputting raw YUV video at 1280 × 720 px resolution and maximum frame rate of only 10 fps. A custom application, based on the gstreamer library, was used to encode the video stream on the fly to the Motion JPEG (MJPEG) video format at a reduced frame rate between 4 and 8 fps; the model 2.0 SNBox's central processor did not have sufficient computing power to process 10 fps. The video was multiplexed with the audio channel from an external microphone (HMU0603C; JL World, Kowloon Bay, Hong Kong) into the Matroska container format, resulting in an MKV video file. Although the CCTV camera included an embedded microphone, we equipped the system with an external microphone, housed in a small plastic tube, placed in the nesting area, and connected to the control unit with a shielded two-core cable with RJ12 male connector.

The processing boards of both models were capable of accepting input from two cameras in one SNBox: a door camera located on the back side of the SNBox and capturing images of the entrance of the next box, and a floor camera placed on the ceiling of the box and directed downward (for details, see Zárybnická et al. 2016). Animal activity triggered recording from one or both cameras, depending on the configuration. In passerine bird monitoring, we usually used only one (floor) camera that provided a good overall view of the nest box interior.

Video time lag and duration

We strove to minimize the trigger delay, that is, the time between detection of animal activity and the recording of the first stored video frame. Since the UVC cameras were not optimized for quick startup, we resorted to continually recording video but not saving video frames to memory until activity was detected. In the model 3.0 SNBox, up to 1 s would be lost due to the properties of the H.264 video format. Therefore, software continually created a 3-second video buffer, whose content was prepended to all video recordings triggered by animal activity, allowing the recordings effectively started 2–3 s before an animal entered the nest box entrance. In the model 2.0 SNBox, the YUV input video format did not cause a delay in production of the first video frame. Here, we did not incorporate the video buffer, resulting in tens to hundreds of milliseconds delay. The length of the video recordings was configurable; based on experience with the boreal owl (Zárybnická et al. 2016), we configured all video recordings to 30 s.

VPN tunnel

A key feature of the SNBox was a VPN tunnel (Fig. 3), because it allowed secure live streaming and remote control. Each computer unit (Fig. 3a) became part of the LAN of each hosting site (via the host's router; Fig. 3c) and ran an OpenVPN client. This VPN client automatically connected to the OpenVPN server running on our university server Ptacionline.czu.cz (a virtual server running on vSphere 6.5, 4xCPU Intel(R) Xeon(R) CPU E5-2680 0 @ 2.70 GHz, 8 GB RAM, 1.7 TB HDD, CentOS Linux 7.4; Fig. 3f), located in the WAN. Each computer unit was assigned its own hardwired IP address. The established tunnel allowed us to perform automated data submission, live video streaming, and remote monitoring and maintenance, which would not be possible otherwise. The VPN client could be easily configured to establish a tunnel to another server, or to be disabled.

Data submission

The SNBox used a custom script based on the rsync utility to automate the submission of recorded data from local data storage to the university server-side data storage (Fig. 3g) through the VPN tunnel, during a configurable time window. The window was set for each SNBox to the time of minimum network traffic for each host's LAN, typically from 22:00 to 04:00 hours. Unsubmitted data were kept on the local data storage for the next submission window, while successfully submitted data were removed to release space for new records. On the university server side, the records were automatically backed up and postprocessed, that is, downscaled and transcoded to video formats suitable for publishing on the webserver, and a thumbnail image of each video recording was extracted, and metadata containing the recording date and time, location, and nesting bird species were saved in the database. The submission script can be easily modified to submit the data to another location (another server, cloud, local desktop), or configured to be disabled for the case of no Internet access.

Data structure

The most critical aspect of data management is creation of an organizational structure that facilitates long-term data integrity and retrieval. We defined the structure of the SNBox non-system files to consist of four top-level directories. The config directory contained configuration files allowing us to customize the video properties (recordings duration), power-saving settings (time of disabled recording), and data submission parameters (start and end time of submission). The events directory stored the video records for each independent activity-triggered event in a separate subdirectory named by its respective timestamp (with an accuracy of one-second). Each such subdirectory contained the video files and a text file with ancillary contextual data (environmental sensor data and exact date and time). The sensors directory contained text files storing the environmental sensor data recorded at a preset interval between the times at which the activity triggered video recording. The log directory contained numerous files with the system debug logs for develop purposes. When submitting to the server, this structure was preserved and further organized in directories named after the box ID and the timestamp of submission, respectively.

Website

The project and collected data are presented on a webserver (Fig. 3h), running on the university server (Fig. 3f), accessible on www.ptacionline.cz and www.birdsonline.cz. The website displays an interactive map of installed SNBoxes (Fig. 4a), and a list and thumbnail image from every video recording available for playback from each SNBox (Fig. 4b). The list is dynamically updated as new records are received and transcoded (model 2.0 only) to the H.264 video format. These videos are categorized by the locality accompanied by the date and time of recording, used for filtering the records. Information on the nesting species inhabiting each SNBox is also listed. Live streaming is not possible from model 2.0 SNBoxes; however, live streams from model 3.0 SNBoxes are available as RTSP protocol links on the website that can be opened by a compatible video player (e.g., VLC). Finally, the website presents general information about the project, its results, partners, and project's presentations in media and provides a registration form for new potential system hosts, all in the Czech and English languages. All material is publicly available to any user without registration (Fig. 3i).

Live streaming

In model 3.0, we used the standard gstreamer implementation of RTSP server to publish the live stream from the cameras. The server used the Real-Time Control Protocol (RTCP) to parameterize and control the stream and the Real-Time Transport Protocol (RTP) to transport the stream. The stream consisted of a H.264 encoded video (1280 × 720 px @30 fps) channel and MP3 encoded audio channel. The live stream was available permanently, and it was not affected by simultaneous video capture. In the LAN, it was possible to play the stream using an arbitrary video player (client) supporting the RTSP protocol, for example, VLC. Multiple clients could connect at the same time. In the WAN, a client could connect to a gstreamer-based retransmission RTSP server, running on the university server. The retransmission server then connected to the RTSP server of the requested camera system

Fig. 4. The public interfaces to this project's Internet accessible data. (a) The website of the Birds Online project, the map of installed SNBoxes. (b) An example of video recordings available on the project's website from the nest hosted on the premises of the Jára Cimrman Elementary School in Prague. The use of live streaming of bird nesting on (c) a projection screen and (d) a desktop computer during biology lessons in elementary and special-needs school, respectively.

via its VPN and started retransmitting the received stream to the client. If multiple clients connected, the retransmission server only duplicated the outgoing stream while receiving a single stream from the camera system, which saved the network traffic and camera system resources.

In the model 2.0, live streaming was not implemented ideally due to gradual development from the model 1.0 software that was primarily designed for stand-alone video monitoring without Internet connection (see *Background*). We implemented custom live video streaming software, consisting of a client (gstplayer) and server (gstsrv), all based on the gstreamer library. Gstsrv ran on the SNBox. A proprietary control protocol provided Video on Demand (VOD) functionality. When gstplayer connected, gstsrv started transmission of a 640 × 480 px MJPEG video stream over the RTP protocol. It was possible to play the stream by gstplayer on any PC inside the LAN (only on a single computer at once), but not over the WAN. Gstsrv ran in a variable time interval (live-stream mode), which was mutually exclusive of event-triggered video capture.

Time synchronization

We needed to synchronize each computer unit's real-time clock so that it did not drift over time. In model 3.0, we used the ntpdate utility to regularly (every 24 h) synchronize the system clock with UTC time, which simplified worldwide data management. The need for automatic time synchronization became clear from our experience with model 2.0 SNBoxes for which we originally synchronized clocks manually, using the local time and respective daylight saving time. Consistent manual management proved impossible, leading to inconsistencies across the installed units. Beginning with 2018, we switched to recording times in UTC in model 2.0 SNBoxes although manual setting of clocks was still needed.

Remote maintenance

We were able to securely connect from the university server to every SNBox at any time using the SSH utility over the VPN tunnel. That allowed remote monitoring and controlling of systems, mainly to change the device configuration and install software updates. The model 3.0 SNBoxes were additionally equipped with an SNMP server, which was regularly queried by Zabbix real-time health monitoring software installed on the university server, for a range of metrics, for example, CPU load, and local data storage availability. Zabbix was configured to send us notification emails in case of triggering conditions for any of the monitored attributes, or in the case of no data being received from a SNBox for more than 12 minutes.

Contextual data analysis

Data are stored on the server using the same directory structure that was created on the SNBoxes (see *Data structure*). While the data were not stored on the server within database software, we still needed some of the functionality of a true database system to allow for the analyses of the contextual data related to each video recording. We implemented two utilities for aggregating and extracting data. Recordextract was a simple graphical tool, used to aggregate contextual data of all captured records (from the events directories) of one or more SNBox camera systems into a single xls (Microsoft Excel spreadsheet) file. Recordextract was written in Perl and distributed with all dependencies as an installer for MS Windows, allowing this script to be used offline by any collaborator performing an analysis on a data subset. Sensorextract was a Linux shell script, used to aggregate all environmental data (from the sensors directories) of a set of camera systems into a set of csv files, one file for each camera system.

Field procedures

We installed and brought into operation all SNBoxes on hosts' premises. After installing the SNBox on tree, balcony or other structure (see *Results*), we connected the control unit with an Ethernet cable to the PoE adapter. The adapter was plugged into an interior 230 V electrical socket within the host's building and connected to the LAN (Fig. 3b). The cable route ran safely, preferentially through the air, in such a way as to present no risk to surrounding traffic or of causing damage to the cable. Afterward, we connected the camera and other peripherals to the computer unit and brought the entire system into operation. The host (or host's IT manager) authorized relevant ports of Firewall protection within their LAN to enable the OpenVPN and local streaming services. We installed a video player (VLC or gstplayer) on a local PC and verified full system functionality. Finally, the host received a short briefing and practical training so that they could understand and maintain the SNBox and watch the live stream. The duration of the entire procedure, including the installation of the wooden box and cable, the device configuration, verification and training, took from 2 to 10 h depending on the local conditions and the host's attitude. Because nesting sites are typically in short supply in the human dominated landscapes in which we installed the SNBoxes, nest boxes are readily occupied and thus we did not explicitly attract birds to the installed boxes.

Costs

The price of the SNBox and associated equipment, including the computer unit, one camera, IR light activity detector, environmental sensors, the external microphone (model 2.0 only), 50 m of Ethernet cable, the PoE adapter, and the wooden box construction reached \$560 without utility costs (all costs in U.S. dollars). This cost was approximately the same for both model 2.0 and 3.0 SNBoxes when produced in low volume. The most expensive components were the computer unit (\$350), the wooden box construction (\$60), the camera (\$60), and the IR light activity detector (\$50). Costs dedicated to the development of the software and hardware through the development of the model 3.0 SNBox (including model 1.0 and model 2.0) reached \$40,000. Additional costs for technical services included the expenses for implementation, operation and maintenance of the university server infrastructure. Although we were able to provide guidelines for self-installation of the SNBox by users, the additional costs associated with assisting in the installation of a SNBox at a new site allowed a new SNBox to come online more quickly, reliably, and safely.

RESULTS

Here, we provide a proof of concept of automated camera nest box monitoring and related networking infrastructure (Fig. 3) that we have designed, refined, and implemented.

Application of smart nest boxes

Between April 2016 and June 2018, we installed and remotely operated 51 SNBoxes that were designed as nest sites for small cavity-nesting passerine birds. Of this total, 33 SNBoxes were equipped with the model 2.0 system and 18 with model 3.0 system (for technical details, see *Materials and Methods*). We deployed the SNBoxes gradually through 2016–2018 (cumulatively 22 SNBoxes in 2016, 33 in 2017, and 51 in 2018) in the Czech Republic and Poland across a 140,000-km^2 region (Fig. 4a), locating the SNBoxes on private premises in villages or towns where Internet and power source were available. Over time, the 51 SNBoxes were placed at a total 64 hosting premises (some SNBoxes were moved once or twice). Of the hosting locations, 44 were schoolyards (preliminary, elementary, middle, high, and special schools), ten were private gardens, four were hospital grounds, three were phenological gardens, two were university grounds, and one was a zoological garden. SNBoxes were most often installed on trees (N = 55 localities), and less commonly on loggias of blocks of flats (N = 4), windows or walls of the building (N = 4), and electric poles (N = 1) at a height of 2–20 m above the ground (mean ± SD, 5.8 ± 2.7 m). The surrounding environments of the nest boxes (buffer radius of 20 m) consisted on average of 57.3% (SD = 22.9) vegetation cover comprised of shrubs, trees, flower beds, and grass area, and 42.7% (22.9) built-up area.

We recoded a total 93 nests in the 51 boxes (median, 25–75%: 2, 0–5 nests per box) across three breeding seasons, although boxes newly installed in 2018 were set out late and thus used at a lower rate. We found two consecutive nesting attempts during the same breeding season in six boxes. The most frequent nester was great tits (N = 64 nests; Fig. 5a–c), followed by Eurasian tree sparrows *Passer montanus* (N = 16 nests; Fig. 5g), European starlings (N = 9 nests; Fig. 5e), Eurasian blue tits (N = 3 nests; Fig. 5f), and common redstart *Phoenicurus phoenicurus* (one nest; Fig. 5d). Moreover, other species such as Eurasian wryneck (*Jynx torquilla*), white wagtail (*Motacilla alba*), house sparrow (*Passer domesticus*), Eurasian nuthatch (*Sitta europaea*), and great spotted woodpecker (*Dendrocopos major*) visited boxes. No nesting of any bird species was recorded from September to February, although birds visited smart boxes sporadically and for a short time, or regularly (e.g., using boxes as overnight roosting locations) throughout the whole year.

Modifications of box wooden construction

In 2018, we modified the SNBox wooden construction to accommodate nesting by common swift (*Apus apus*; Fig. 5h) and little owl (*Athene noctua*), and we recorded that both species visited (but not immediately nested in) the boxes soon after the SNBox installation.

Data acquisition

The 51 SNBoxes were in operation for 18,533 d (521 ± 261 d for each model 2.0 SNBox, and 75 ± 16 d for each model 3.0 SNBox). These SNBoxes recorded and transferred data on 16,776 nest box-days (89.9% of installed days, 472 ± 239 d per model 2.0 SNBox and 67 ± 17 d per model 3.0 SNBox). The speed of a host's Internet connection was crucial for determining the performance of a SNBox. Specifically,

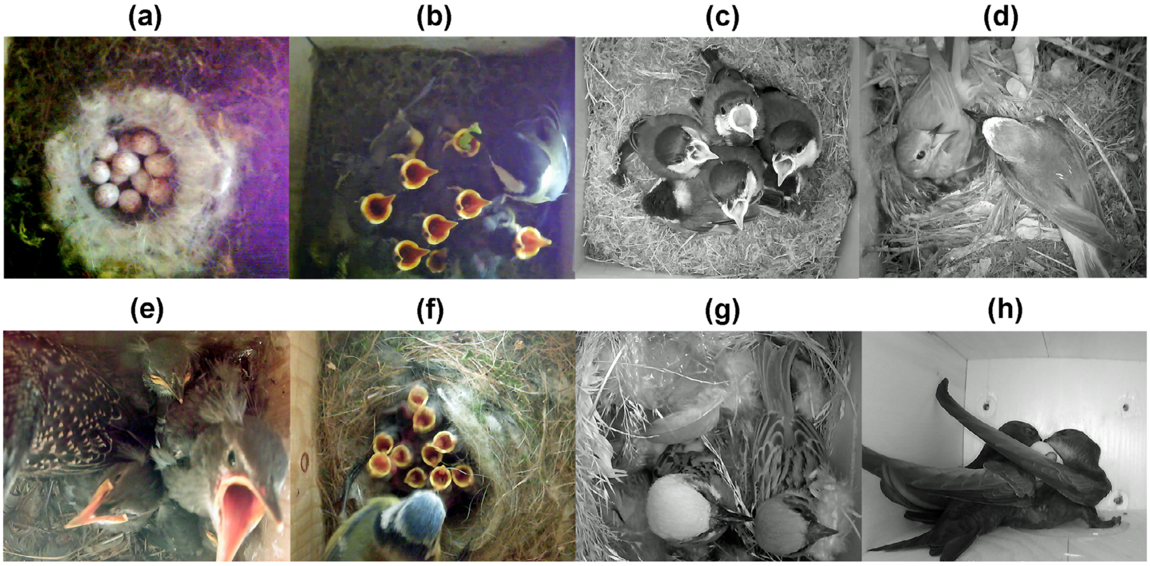

Fig. 5. Examples from videos recorded by the camera system of the SNBox: still image of (a) a clutch of great tit (*Parus major*) eggs, (b) a parent great tit feeding the nestlings, (c) great tit nestlings, and (d) an incubating female and male parent common redstart (*Phoenicurus phoenicurus*) recorded by the model 3.0 camera system. Photograph of (e) begging nestling European starlings (*Sturnus vulgaris*), (f) Eurasian blue tit (*Cyanistes caeruleus*) nestlings with a parent, (g) parents of Eurasian tree sparrow (*Parus montanus*) with the nest material, and (h) courting common swifts (*Apus apus*) recorded by the model 2.0 camera system.

we found data recording and transfer most often failed due to insufficient Internet bandwidth (50% of failure days). A minimum upload bandwidth of 6 Mb/s was needed for successful livestream transmission to the server, and 2–3 Mb/s average speed was required to submit a day's collected data to the server overnight. A local data storage capacity of 16 GB was sufficient for video recordings of all daily activities in every nest. However, at the hosting localities where Internet bandwidth fell below the minimum requirements noted above, the video records started to accumulate in local data storage, and when storage capacity was exceeded, the SNBox started to behave unexpectedly. Connection speed and upload limits were mainly important during the nestling and fledgling periods as parental activity (mainly feeding frequency) increased. Another reason for failure of the system was the interruption in either the supply of Internet or power connection to a SNBox from the hosting site (40% of failures). In rare cases (10% of failures), the camera system failed due to inclement weather or insect activities. For example, water penetrating into one Ethernet cable caused a short on the power supply or insect larva blocked the IR light activity detector initially causing false detections and ultimately no detections. However, we were able to detect system failures rapidly (systems sent automated status reported every 12 min) using real-time monitoring software.

From April 2016 to June 2018, a total 631,331 short video recordings (each record usually 30 s in duration) totaling 8649 GB were remotely transmitted from the 51 smart boxes. On average, 60.1 (SD = 124.6) and 809.3 (1696.8) video recordings, that is, 0.8 (1.6) and 11.1 (23.4) GB in size, were transmitted from each box per day and month, respectively (Fig. 6a, b). Video recordings from all SNBoxes were transmitted automatically every day starting at 22:00 (local time), and all submitted video recordings were published on the project's website with a one-day delay. Installed SNBox locations were represented as icons on an interactive map (yellow for model 2.0 and red for model 3.0; Fig. 4a) referencing to the SNBox details, including a list of all

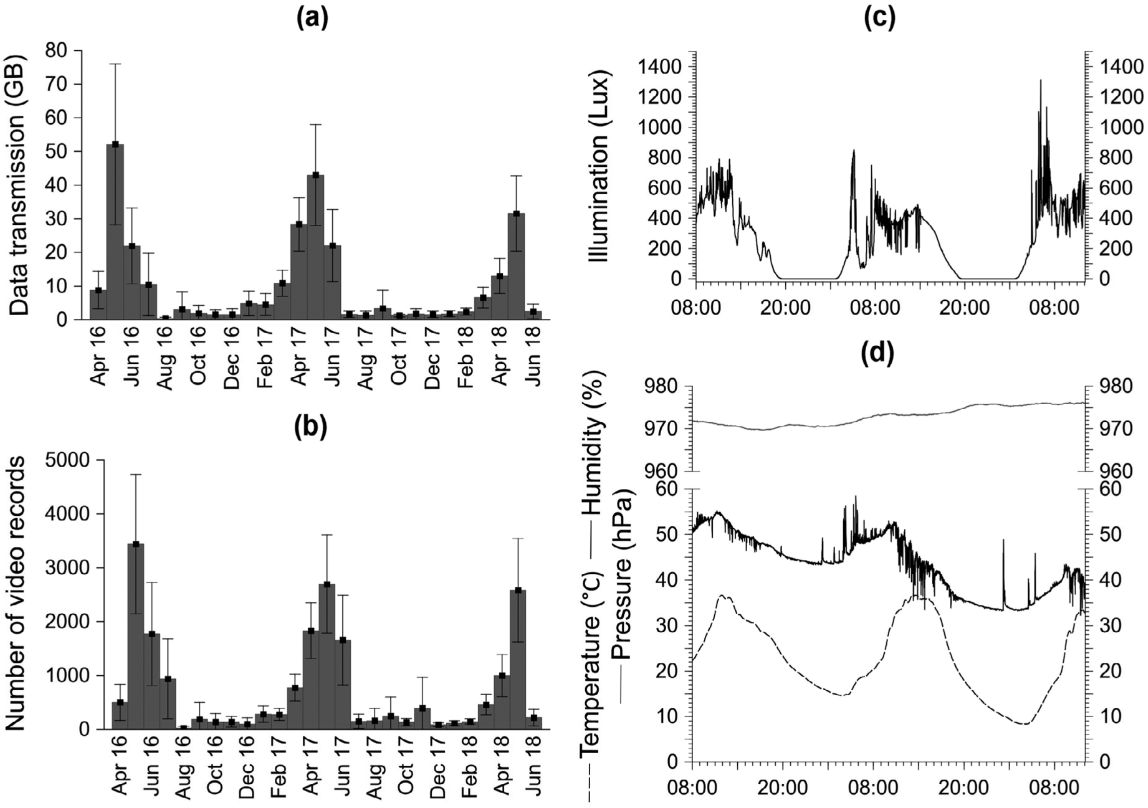

Fig. 6. Rates of data acquisition using SNBoxes and examples of data collected by environmental sensors embedded in the SNBox. (a) Mean monthly volume of data (GB) and (b) the number of video recordings transmitted from each SNBox (mean ± SD) to the university server between April 2016 and June 2018. Examples of data recorded by environmental sensors in one model 3.0 SNBox (at 30-s intervals) from 29 May (08:00) to 1 July (12:00); (c) illumination intensity (Lux), and (d) temperature (°C), air pressure (hPa), and humidity (%).

video recordings (animal activities) categorized by date and displayed by thumbnails (Fig. 4b), and nest statistics. Model 3.0 live streams were published on the website, and model 2.0 live streams were provided via gstplayer to host sites only. Anybody could watch or download any video recording, and all material presented was freely available to the public.

Video recording quality

Generally, the quality of video was sufficient for extracting desired biological information but it was sometimes less suitable for comfortable watching due to the low light levels inside the nest boxes. The video quality mainly fluctuated due to varying light conditions during the daytime, depending on bird species, and the nesting phase. Monochrome video provided bright and clear picture while color videos were often dark, especially during dawn and dusk when low levels of natural light occurred but before being dark enough to trigger the camera to turn on its IR lighting. Bigger and darker birds (e.g., European starlings) absorbed large portions of light inside the box, which resulted in lower-quality video recordings. In bird species that build high nests (e.g., Eurasian tree sparrows), the nest material almost completely covered the translucent windows in the sides of boxes, which limited the input of daylight into the box. Finally, objects relatively close to the ceiling were also blurred due to the distance at which cameras' focus had been set.

We found different limitations for the video quality in the models 2.0 and 3.0 as results of using of different types of cameras (with different video format) and computer units. In particular, neither of the camera types allowed control of the IR lighting or automatic focusing. The model 3.0 camera produced significantly darker daytime video than model 2.0 camera, although we tried to optimize the camera settings for gain, brightness, and contrast. On the other hand, during nighttime video recording, when IR lighting was switched on, the model 3.0 boxes' cameras produced video of higher quality thanks to their higher frame rate (30 vs. 6 fps). In the model 2.0 SNBox, jerky and motion-blurred video recordings were produced (mainly when older nestlings moved rapidly) due to low video frame rate caused by insufficient processing power of the computer unit and the camera video format. As a result, model 3.0 cameras produced smooth but sometimes dark video recordings (Video S1), while model 2.0 records were brighter but jerky and motion-blurred (Video S2).

Environmental sensors

Together with each video recording, we collected the information on the external temperature (°C), relative humidity (%), air pressure (hPa), and light intensity (Lux; Fig. 6c) from the sensors of model 3.0 SNBoxes and recorded external temperature (°C), light intensity index (dimensionless values), and inside temperature from the model 2.0 SNBoxes' sensors. In addition to recording environmental data each time a video recording was made, these same environmental measures were made at 30-s intervals even when the camera was not activated.

Based on examining these environmental data, we realized that the appropriate placement of some environmental sensors requires testing in order to insure that sensors are recording the information that is required. As one example, we found that the hygrometer in the model 3.0 SNBoxes was not recording the information that we had assumed. Specifically, we found that measurements of relative humidity increased with increasing temperature (Fig. 6d), while we expected that relative humidity would correlate negatively with temperature. Ad hoc testing after we removed the protective wooden plank covering the sensors and their circuit board produced the results that we had expected. As a second example, measurements from sensors in the model 2.0 were technically reliable; however, the location of external temperature and light sensors, on the sidewall of the SNBox, resulted in variation in measurements both within and among nest boxes as a result of proximity of vegetation blocking light to varying extents.

Biological data

We gathered a huge collection of video data that provided us with a wide range of biological information on bird nesting activities and behaviors over time (Fig. 5; Videos S1, S2). We obtained information such as clutch size, the duration of nest building, egg incubation, hatching and fledgling periods, as well as clutch and brood attentiveness (i.e., the proportion of time that eggs were incubated and nestlings brooded by parents), feeding rate, and hatching and fledging success. We also monitored covering of the clutch with nest material during incubation off-bouts, eating and removing nestling fecal sacs by parents, sibling competition between nestlings and fledglings, and parental communication and cooperation. We were able to determine the composition of nestling material, as well as the prey items brought by parents to their nests with varying degree of precision and levels of taxonomic resolution. For example, based on preliminary video processing of two nests monitored by the model 2.0 SNBoxes, we determined the development stages (i.e., larva or adult) and taxonomic group for 45.0% and 24.2% of all food items in a nest of great tit and European starling, respectively (Table 2). We also found that European starling parents delivered to their nestlings multiple food items at once, while great tit brought separate prey items. Finally, the SNBox allowed us to monitor animal activities inside the box throughout the whole year, thus including avian roosting activities. To date, the processing of video recordings has been manual, although we are exploring the potential for automating some of this processing (see *Discussion*).

Educational opportunities

Information from our nest boxes was also turned into educational materials and enabled members of the general public to build a better understanding of the natural world, and of scientific research. For example, the teachers at elementary or middle schools introduced live

Table 2. The precision and the levels of taxonomic resolution of food items delivered by different bird species to the SNBoxes that were achieved based on human manual identification.

Class/subclass and order/ suborder/superfamily/family	Great tit						European starling					
	Number	%	Larva	%	Adult	%	Number	%	Larva	%	Adult	%
Insecta/Pterygota	195	39.7	194	39.5	1	0.2	243	6.4	218	5.7	25	0.7
Coleoptera							3	<0.1	1	<0.1	2	0.1
Coleoptera: Cantharidae	1	0.2			1	0.2						
Coleoptera: Chrysomelidae	1	0.2	1	0.2								
Coleoptera: Curculionidae	3	0.6			3	0.6						
Dermaptera	1	0.2			1	0.2						
Diptera							430	11.3	428	11.2	2	0.1
Diptera: Bibionidae	1	0.2			1	0.2						
Diptera: Bombyliidae	2	0.4			2	0.4						
Diptera: Brachycera	7	1.5			7	1.4	2	<0.1			2	0.1
Diptera: Nematocera							2	<0.1			2	0.1
Diptera: Tipuloidea	1	0.2			1	0.2	46	1.2	2	0.1	44	1.2
Ephemeroptera							3	<0.1			3	0.1
Hemiptera: Heteroptera	1	0.2			1	0.2						
Hemiptera: Pentatomidae	1	0.2			1	0.2						
Hymenoptera: Apoidea	3	0.6			3	0.6						
Hymenoptera: Ichneumonidae	1	0.2			1	0.2						
Lepidoptera/Hymenoptera	1	0.2	1	0.2								
Lepidoptera	2	0.4			2	0.4	150	3.9			150	4.1
Lepidoptera: *Agrotis exclamationis*							22	0.6			22	0.6
Lepidoptera: Lycaenidae							2	<0.1			2	0.1
Lepidoptera: Nymphalidae							1	<0.1			1	< 0.1
Odonata							2	<0.1	2	0.1		
Odonata: Zygoptera							2	<0.1			2	0.1
Orthoptera	1	0.2			1	0.2						
Orthoptera: Caelifera							1	<0.1			1	< 0.1
Gastropoda	1	0.2										
Stylommatophora	1	0.2										
Malacostraca												
Isopoda							3	<0.1				
Chelicerata	1	0.2										
Araneida	40	8.2					5	<0.1				
Araneida: Pholcidae	3	0.6										
Araneida: Thomisidae	1	0.2										
Opilionida	1	0.2										
Annelida												
Oligochaeta							5	<0.1				
Unidentified	221	45					2885	75.8				
Total	491	100	195	39.7	26	5.3	3807	100	651	17.1	258	7.1

Notes: Examples of food types (both developmental stages and taxonomic groupings) delivered by great tit (*Parus major*) and European starling (*Sturnus vulgaris*) parents to their nestlings during the incubation period (N = 19 d, N = 1 nest) and the incubation and nestling period (N = 37 d, N = 1 nest), respectively.

video streaming of bird nesting on interactive screens or laptops into lessons on the environment and biology (Fig. 4c, d). Schoolchildren painted pictures, wrote bird stories, and created handcrafts about birds, and older students created video clips about bird nesting and helped to produced wooden nest boxes. Finally, schoolchildren with alternative home schooling and university students analyzed video data to gain biological information about nesting process, and while schoolchildren presented the results in their classrooms and in public, university students used these data in their bachelor and master theses.

Discussion

Animal video monitoring is an important methodological tool for acquiring reliable information on ecology and behavior of animals in their natural environments, for relatively low financial cost and human effort. While off-the-shelf camera systems are readily available, we have shown here that the extra effort of developing a custom-designed camera system and related networking infrastructure can both greatly expand the range of data collected and facilitate facets of data management that include the following: sharing audiovisual information in real time and retrospectively, filtering the live stream of video to only store segments of interest, remotely managing camera systems, and integrating all forms of data within a comprehensive data storage system. Our own principal design goal was to create a system in which audiovisual information could be shared for research as well as educational purposes. Below, we discuss the major design decisions that we made in developing our system, provide examples of potential research and educational uses of these data, and offer suggestions regarding the trade-offs involved in designing any such system.

Designing a system to match research objectives

In designing our own third-generation SNBox system, we wanted to place our camera systems in urban areas, for both research and educational purposes. We will use the example of urban ecological research in order to present examples of how starting with research and educational objectives led us to design our current SNBox system. Urbanization affects many aspects of birds' environments: vegetation type and structure (Chamberlain et al. 2009, Bailly et al. 2016), climate (Charmantier et al. 2008, Irons et al. 2017), biogeochemical cycles (Ligeza and Smal 2003), water and atmosphere contamination (Bauerová et al. 2017), the availability of food source (Isaksson and Andersson 2007, Chamberlain et al. 2009), light (Titulaer et al. 2012, Dominoni et al. 2014), noise (Shannon et al. 2016, Injaian et al. 2018) pollution, and biodiversity including predator community structure (Sandström et al. 2006, Chamberlain et al. 2009). Nest box cameras, by themselves, readily provide information relevant for research into effects of urbanization that includes investigations of the structure of diet including prey type and prey size (Nour et al. 1998, Garcia-Navas and Sanz 2011); parental time investment in incubating eggs or brooding nestlings (Tripet et al. 2002, Matysioková and Remeš 2010), feeding rate, and nest-visitation rate (Isaksson and Andersson 2007, Titulaer et al. 2012); and sibling competition (Neuenschwander et al. 2003). Any camera of reasonable resolution would be able to gather data appropriate for research into the topics listed above. However, our decision to network our SNBoxes and especially to automate data management made the images a readily accessible source of data with which we could engage undergraduate students in research projects in urban ecology such as an examination in diet shift in which urban great tits were found to react to increased food demand from their nestlings by bringing greater proportions of a non-native and invasive *Cydalima perspectalis* larva that contain toxic alkaloids, documenting reductions in incubation time with warmer environmental conditions, and revealing adjustments in the types of nest material used in relation to its availability in local area (M. Zárybnická, *unpublished data*). The use of wired Internet and power connections also allowed us to operate our SNBoxes year-round with very little ongoing cost, enabling us to document the use of nest boxes outside of the nesting season as roosting sites (Fig. 6a, b). Systematic accumulation of anecdotal uses of nest boxes as winter roost would through time allow the examination of behavioral decisions regarding overnight roosting sites, for example, with variation in thermal and light environment (Villen-Perez et al. 2014).

Research into topics such as the effects of ambient temperature on incubation rhythm or winter roosting depends on the collection of ancillary data that complement the camera images. The ability to have such ancillary data collected and managed by the same system that acquires and manages images is another benefit of working with the system that we designed. We have already incorporated a variety of environmental sensors in the system such as a thermometer, hygrometer, barometer, magnetometer, luxmeter (light-level measurements), and an external microphone (for noise pollution measurement). These sensors together cost only roughly $40 per nest box. The range of sensors can be extended or modified according to research objectives, by incorporating sensors that measure environmental features such as precipitation, wind, NO_x, CO_2, CH_4, LPG, and dust. In addition to environmental measurements, other sources of ancillary data can be gathered. For example, we have matched information on the identities of boreal owls with their images based on attaching PIT tags on boreal owls and incorporating an RFID tag reader into the entrance of our first generation of SNBox (Zárybnická et al. 2016). We have also designed and developed a scale to weigh nest contents and an infrared thermometer for contactless measurement of temperature of the clutch and nesting material (Šálek and Zárybnická 2015), as well as the external speaker connected to the computer unit in order to conduct acoustic experiments (Injaian et al. 2018).

More important than any of the specifics of these examples are three general observations. First, there are potentially major benefits to creating a custom-designed nest box monitoring system in that research objectives can be allowed to drive design in order to collect data that are better matched to research objectives. Second, a custom-designed system can facilitate data management post-collection: Images and ancillary data can be automatically tagged to allow the various sources of data to be associated with each other. Third, with a real-time Internet connection all of these data can be automatically uploaded to and stored within a database management system, thus eliminating the potentially substantial costs of human effort in manual data management.

Designing a system to match educational objectives

The educational potential of information from our SNBoxes was a major motivation behind the nest box system that we designed. Non-invasive remote monitoring of nests only required the installation of a SNBox, allowing individual people to develop a connection with research by hosting a SNBox as long as they can provide a site and Internet connection for a SNBox location. Outputs from video monitoring provide even greater opportunities for formal and information education. We have used output from our SNBoxes to enable teachers at schools of all grades to introduce educational materials such as live video streams and video recordings during science lessons. These materials were used by teachers to supplement generic textbook information with real-life bird observations. These school activities varied with student ages and included creating pictures, stories, handcrafts, and video clips, as well as the extraction of biological information from video recordings and its presentation in classrooms (for details, see Zárybnická et al. 2017). Students in more advanced grades at vocational training schools have developed their technical skills in material, machining, and producing documentation in the course of making wooden boxes used for our SNBox system.

We also saw outputs from our SNBoxes being used in a range of informal education settings. Most basically, to date over 50,000 unique individuals or groups from over 100 countries have viewed the live streaming or archived videos, based on Google Analytics. Teenaged students engaged in at-home educational activities that included extracting biological information from video recordings and making public presentations including amateur ornithological conferences and on television news programs. The use of output from the SNBoxes is not, however, limited to educational institutions. Other organizations such as hospitals and other healthcare services have installed the SNBoxes on their grounds and use the systems to engage a wide audience and provide opportunities for disabled and disadvantaged people within a citizen science project.

All of the potential educational uses, both formal and informal, rely on readily accessible output from nest box cameras, which enables people to connect with nature wherever they have access to network infrastructure. While locally networked cameras only allow this opportunity within host's premises, sharing information through the Internet enables for far wider educational benefits.

Custom designing nest boxes for camera systems

Even the design of the nest box itself needs to be evaluated for use with a camera system. The standard nest boxes used for studies of cavity-nesting bird species (Vaugoyeau et al. 2016) require that the camera and related electronics are mounted outside of a typical nest box (Prinz et al. 2016). We made the decision to create custom-designed wooden nest box in order to protect the whole camera system against inclement weather conditions (e.g., rain, sunlight), dust, insect activities, and human interference (i.e., vandalism, theft). Given a basic design of the housing of sensor and computer systems, boxes can be adapted to the needs of individual bird species. We developed specialized wooden bird boxes for nesting common swift and little owl that were occupied soon after their installation. Custom designing of nest boxes also allowed us to place environmental sensors where we wanted them to be, although we found through experience that sensor placement needs to be planned carefully (see *Results*, above, for details). Custom designing our nest boxes also allowed us to embed a small frosted window to illuminate the interior with natural light and allow our camera to record in color rather than monochrome while avoiding the need for artificially illuminating the interior of the nest box. Although the construction of our custom-designed SNBox increased the cost of the nest box (the approximate cost of a single nest box was $60), we found the benefits in the form of easier hardware maintenance when the SNBox was installed in the field, and the greater protection of electronics allowed our system to operate throughout the year under all weather conditions to which the boxes were subjected.

Custom-designed computer unit

Central to our design for the SNBox was our decision to base the electronic systems around a custom-designed embedded computer with a relatively sophisticated microprocessor (see *Materials and Methods*, above, for details). By doing so, we were not constrained by any limitations imposed by hardware and software in lower-cost, off-the-shelf systems (Prinz et al. 2016). The most expansive component of our system was the custom-designed computer unit ($350), used in lieu of a cheaper single-board computer such as the Raspberry Pi ($35). The Raspberry Pi is primarily designed for learning of electronics programming rather than professional applications (for details, see https://www.raspberrypi.org). Thus, these inexpensive devices have the following limitations: no on-board memory for storage, no possibility to run Linux and a real-time operating system (RTOS) in parallel (allowing the combined advantages of a feature-rich operating system together with minimum latencies and full control of a real-time operating system), no real-time clock, limited hardware inputs/outputs, unreliable physical connectors without locks, no optimization for low power consumption, no qualification for operation under challenging environmental conditions (e.g., below 0°C), potential challenges for finding suitable housing, and lack of guarantee of long-term support and production (production is only guaranteed through 2023; see https://www.raspberrypi.org).

We also greatly appreciated the flexibility that our SNBox computer enabled for configuring the timing of active operation (i.e., continuous operation or operation during a subset of time each day) and lengths of archived video clips, as well as the possibility of equipping each nest box with either one or two cameras. We could remotely set and adjust video recording for specific species and tasks. For example, we could set the duration of video recordings to balance between constraints of finite local data storage capacity and the amount of biological information that we wanted to collect, and we adjusted this setting through the course of nesting attempts (i.e., from nest building and egg laying to fledgling period). We could also decide whether to use the door camera pointed toward the nest box entrance and/or the floor camera viewing nest area at any point in the nesting cycle. The door camera was usually more appropriate for gathering information on larger bird species, such as boreal owl, that spent some time (usually about 1–2 s) in the nest box entrance while transferring prey to its mate inside the box, while the floor camera view of nest content for owls was limited because a parent owl usually covered the nestlings, eggs, and prey with its body (Zárybnická et al. 2016). In contrast, floor cameras were more suitable for monitoring small passerine birds that usually entered the nest box rapidly with no time spent at the nest box entrance, and bird activities, including food handing and feeding the nestlings, were more reliably seen from above.

Criteria for camera selection

We found that the choice of camera modules requires careful consideration, for multiple reasons. The type of camera influenced the quality of video and format in which video was encoded, the latter affecting compatibility with video player software. In two SNBox models, we used two similar types of commercial cameras from the same supplier that differed only in video encoding and factory calibration. Overall, both camera models produced video of sufficiently high quality to gathering required biological information. However, each of the two models that we used had some limitations related to the quality of data that were available. First, neither of the cameras was capable of automatic focusing and only manual focusing in situ was possible, which prohibited adjustment of the picture sharpness in the course of a nesting attempt. Both camera models were hardwired to begin using IR lighting (and recording of video in monochrome) at unalterable levels of available light. The result was overly dark video being produced at dawn and dusk, when low levels of natural light occurred while the IR lighting was turned off. There was no documented way for user configuration of the light level at which IR illumination would start. Further, the camera module used in the second version of our nest boxes produced jerky and motion-blurred video, mainly when older nestlings moved quickly. This problem was caused by a combination of the camera's native video format and insufficient computing power of the computer unit (model 2.0) for transcoding the video into a different format at a sufficiently high frame rate. Additionally, it was only possible to transcode the stream to the MJPEG video format, which had to be further transcoded on the server to H.264 video for publishing on our website. This issue led us to upgrade both hardware and software in the third version of the SNBox. The newer camera module (model 3.0 SNBox) produced higher-quality video due to the higher frame rate of 30 fps, which additionally was already encoded in the widely supported H.264 codec. However, the newer camera module, although featuring the same image sensor, produced darker video due to different calibration in the factory. While we have not yet found an ideal camera module, it is clear that there are multiple factors that need to be taken into consideration when choosing an appropriate camera module: maximum resolution and frame rate, output video format, control interface, sensor chip sensitivity, day/night mode switching, IR lighting and its control options, lens focusing, the presence of an embedded microphone, and housing. For future development, we would like to find a camera module in which we could alter the configuration of the day/night camera sensor to turn the IR lighting at higher levels of ambient light. We could also try to find a camera with even more sensitive sensor. Alternatively, we would dispense with recording color video entirely, as the monochrome recordings were of superior quality for most of our intended uses.

Power input and data output

Although our SNBox system was relatively expensive to design and produce (see *Materials and Methods*, above, for details), it has provided continual live streaming, extensive video material on breeding and roosting phenology of birds, and a variety of ancillary data on local environmental conditions and animal phenology. The costs for off-the-shelf camera technology would be substantially lower; however, such systems would never provide such a wide range of research and educational opportunities as a custom-designed system such as ours. Here, we consider trade-offs between use of off-the-shelf camera and custom-designed systems and provide suggestions for different strategies in (1) data acquisition and (2) system powering. We are treating these two together, because in our experience they are interrelated.

Off-the-shelf camera systems have the advantage of providing a fast and simple technical solution requiring no specific technological modifications of devices, allowing continual video monitoring (or monitoring during a subset of time each date) potentially with the addition of a motion detector or IR lighting which are widely available in commercial camera traps (Trolliet et al. 2014). Off-the-shelf systems are also convenient when there is no need for data archiving (i.e., only live streaming), or any archives are small and data management can be performed manually. Examples of uses fitting these constraints are for individuals and the public who want live streaming of bird nesting (e.g., View Nesting Birds portal; see https://www.viewbirds.com), or researchers who collect limited biological data, such as estimating animal distribution using camera traps (Trolliet et al. 2014), or feeding rates of nesting birds using video filming (Nour et al. 1998). In contrast, the custom-designed camera technology is more appropriate for researchers who need specific data (e.g., high-speed video recording; Rico-Guevara and Mickley 2017) or require complex biological data (Matysioková and Remeš 2010, Zárybnická et al. 2016) from either long-term monitoring in natural environmental conditions or the collection of data additional to video.

Both off-the-shelf and custom-designed systems can be powered by electricity from different sources (i.e., directly from electrical networks or stand-alone) and use different processes for moving data from systems into a data archive (i.e., through Internet-connection or offline, manual transfer). Stand-alone camera monitoring typically uses battery powering and is necessary in areas without power source availability, such as for monitoring species living in forest and non-urban habitats. Such systems are usually operated offline, that is, without Internet connectivity (Bolton et al. 2007, Cox et al. 2012). This typically leads to the need to download the data in situ manually and regular battery replacement (usually each 5–8 d; Bolton et al. 2007, Zárybnická et al. 2016), either of which can disturb nesting birds. Offline systems do save the costs for connectivity and cloud services, although they prevent the sharing of data via Internet in real time and increase costs for regular field maintenance. The decision to use stand-alone camera systems has to balance between biological profit and financial costs for field maintenance that likely will limit the range of research activities in time and space (e.g., only during nesting period of birds and in a limited area). We believe that in the future, the principal challenge for developing offline systems will be in adapting them for use with affordable alternate power sources such as solar cells for recharging batteries. Among the requirements will be dealing with low light levels as would be found in forest habitat, the larger physical sizes of systems, and the resultant potentials to attract undesirable human attention or distract animals.

We believe that the Internet-connected camera systems, based on a wired or wireless connectivity, allow for the greatest flexibility for monitoring animals in nest boxes. This approach currently requires relatively high costs for initial development and technical support that must be balanced with multiple benefits for researchers and other people as well as the animals being monitored. Internet-connected nest box systems do impose specific technological and infrastructure challenges. In particular, we found that the availability of a reliable Internet connection is critical. The main reason for the failures of our SNBoxes (they were unavailable only 10% of the time) was most often the result of unstable or low speed of local Internet connection (50% of instances). Thus, the quality of Internet connection should be assessed prior to planning to use Internet-connected systems, and simultaneously, automated health monitoring software should be deployed, as we found it very efficient for detecting system failures. In future developments, wired Internet connections could be replaced by wireless (e.g., WiFi or GSM network) data transmission. The technical challenges to overcome in order to make this practical include the following: speed of wireless connection that can vary through time, increased power consumption, and limitations of cellular data transmission rates in more remote areas. The transmission of large volumes of cellular data can also be relatively expensive.

Even where wired electrical and data transmission is possible, the distance from a power or network connection is limited. Wire-connected systems cannot be too distant from a power socket (e.g., Power over Ethernet is usually limited to 100 m due to Ethernet protocol limits), their installation is more complicated, and cables can be interrupted (40% of failures of our camera system were caused by the physical interruption of cable connectivity). Further, potential safety issues might exist without careful design, such as issues of property safety (e.g., missing galvanic isolation might be an issue), and network system security for the data-management system could potentially be compromised as authentication mechanisms are not common in cable networks.

The safety and security issues could be resolved with appropriate hardware and software development.

Future development

In this paper, we have considered the challenges involved in acquiring and sharing video and other information with which to study nesting birds. We anticipate that the greatest future challenges will be in turning the raw video into useful biological information. First, data storage needs to be considered given the large volumes of data that can be collected (we collected 8649 GB of video data over 16,776 observational days). General-purpose cloud service such as Microsoft Azure or Amazon Drive may prove to be the most practical solution, although potentially high costs of downloading data from cloud archives need to be considered carefully. We suspect that data processing will be more challenging than data archiving. The costs and benefits of human processing of raw data need to be explored, including the potential use of well-established crowdsourcing platforms such as Amazon's Mechanical Turk (Buhrmester et al. 2011), Prolific Academic (Peer et al. 2017), or the citizen-science-oriented Zooniverse (Borden et al. 2013). The costs and benefits of human processing need to be weighed against the development of automated processing pipelines for this same information, such as the use of machine vision algorithms for the automatic classification of the video content (Weinstein 2018). We believe that automation could facilitate extraction of data on such features as the number of eggs and nestlings, and the type of food and bird activity.

More generally, we see the development of custom-designed data-collection systems, coupled with methods for processing the large volumes of data that can be collected, having wider applicability in population ecology. This is especially true as the intended scale, either spatial extent or time period, increases. In this context, the specific decisions that we have made in the design of our SNBox system are illustrations of the need to think about all aspects of an entire system, from defining goals, to identifying components of a system, through to careful consideration of the specifications of each component in a system.

ACKNOWLEDGMENTS

We are grateful to P. Junek for the help with developing the project's website. We also thank J. Kubizňák, J. Bartoška, and V. Hlaváč for technical support; J. Hruška for designing the project's logo and website; J. Hlaváčová, R. Kočiš, M. Vašica, E. Bernardová, L. Vanická, M. Baníková, M. Šejnová, Z. Borna, and other host's applicants for their assistance with the SNBox installation; V. Kerdová, A. Králíková, and other students for the help with data analyses; and M. Hrdý for video montage. This study was funded by the Operational Programme Prague – Growth Pole of the Czech Republic (CZ.07.1.02/0.0/0.0/16_023/0000111), the Czech University of Life Sciences Prague (CIGA 20144203, 20164202, 20174203), and Česká spořitelna a.s. (99200/1710/7133).

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Supporting Information

Additional Supporting Information may be found online at: http://onlinelibrary.wiley.com/doi/10.1002/ecs2.2761/full

Chapter 5

System Design

We have developed and tested a total of three models of a custom-designed camera system for nest box monitoring, so-called Smart Nest Box (SNBox).

The models differed, besides other properties, in support of powering and connectivity modes of operation. The system can be either mains-powered, meaning it has a stable power supply from mains, or battery-powered, meaning it is powered by a battery that has to be replaced and charged regularly. Regarding connectivity, the system can be either operated online, meaning it is permanently connected to the Internet, functioning as an IoT device, or it can be operated offline, meaning without connection to the Internet, requiring the user to regularly download the data on-site.

5.1 Model 1.0

The first model (model 1.0) was developed in 2014 and is described briefly in **Zárybnická, Kubizňák, et al. (2016)** and closely in Kubizňák (2014). It was purpose-designed as an advanced tool for scientific monitoring of Tengmalm's owl (*Aegolius funereus*) nesting in the Ore Mountains, Czech Republic. The device was equipped with two monochromatic industrial cameras with infrared (IR) light, capable of night vision. The cameras produced video in a resolution of 1280×1024 pixels (px), with up to 10 frames per second (fps). Video recording was triggered by an event detector in the form of an IR light barrier placed in the nest box opening in such a way that the beam crossed the opening horizontally in the middle. The trigger speed was 16 ms. To ease recognition of the individuals, the opening was fitted with a circular antenna, connected to an embedded Radio-Frequency Identification (RFID) reader, which scanned the RFID tag of the bird passing in the nest box. The device was further equipped by two thermometers for interior and exterior temperature measurements, and a light intensity sensor to measure degrees of darkness. The system was battery-powered by a 12 V battery and only offline operation was supported, with all data being stored on a 4 GB MicroSD card. Regular maintenance (every 6.5 days, SE = 0.15, N = 56) was required to replace the battery and download the data using File Transfer Protocol (FTP) client software. The cost of the whole system reached $1,400, which was mainly caused by using expensive industrial cameras (purchase price of $326 each) **(Zárybnická, Kubizňák, et al. 2016)**.

5.2 Model 2.0

The second model (model 2.0), briefly described in **Kubizňák et al. (2019)**, was developed in 2016 to address the main drawbacks of model 1.0, i.e. high cost and uncomfortable maintenance. The main intention was to make it an IoT (online-operated) device that would allow the automatic collection of video, audio and textual data on animal behaviour, including automatic data submission, storage and sharing through the newly introduced university server (see Chapter 5.4), hence achieving better project scalability.

The computer unit was redesigned to (1) allow mains-powered operation, (2) simplify installation, and (3) reduce the cost. The terminal strip of model 1.0 was replaced by a set of RJ12 connectors, that are cheaper and much easier for installation in the field. The board was fitted to a simpler housing that on one hand provided worse Ingress Protection (IP) compared to model 1.0, but was cheaper and easier for installation. The computer was based on the same microprocessor to keep the hardware highly compatible with model 1.0. That allowed reusing most of the software and hence saving development costs.

The main change laid in replacing the expensive industrial cameras by a cheaper alternative. I chose colour Closed-Circuit Television (CCTV) Universal Serial Bus (USB) camera (purchase price of $27 without additional costs) with IR light and automatic switching between the day and night modes according to scene illumination. It allowed the system to produce colour video records during daytime and at dusk, and greyscale records in the dark. It produced raw YUV video at 1280×720 px (720p) resolution. I implemented a custom application to fetch the data from the camera, encode it on the fly to the Motion JPEG (MJPEG) video format with 4-8 fps and multiplex it with the audio channel to the Matroska container, resulting in an MKV video file. The low frame rate was caused by the insufficient processing power of the control unit performing the conversion, which was required to reduce the size of the video files, save space on the MicroSD card and reduce network traffic. Anyway, the MJPEG format was not suitable for playback in a web browser, resulting in the need to transcode each submitted video again on the university server, which consumed a high portion of server resources, limiting project scalability.

Additionally to the activity-triggered recording, the new application was capable of live streaming of the camera video. It was possible to play the stream in a dedicated proprietary video player, installed on a desktop computer in the Local Area Network (LAN), but it was not possible to play the stream on multiple computers at once. I also implemented an experimental transcoder to be run on the university server to provide the stream to the public but its capabilities were limited and not scalable. Moreover, it was not possible to produce activity-triggered records when live streaming was enabled.

For the purpose of SNBox installation, we have used the Ethernet cable connection. Its main function was to provide the Internet connection, which was required for automatic data submission and remote system configuration. Along with the data, it also passed the electric power to the control unit. This technique is called Power over Ethernet (PoE). Stable power delivery and maintenance-free data submission allowed us to apply a significantly higher number of SNBoxes compared to the battery-powered systems of model 1.0. From a technological view, the cable connection has proven to be an ideal, cheap and highly reliable solution. Despite these advantages, it was not friendly to the applicants in the sense of placement of the cable route through the applicants' premises, usually including windows (without destruction), and its installation was time-consuming (usually 2-4 hours).

5.3 Model 3.0

The third generation (model 3.0) of SNBox, briefly described in **Kubizňák et al. (2019)**, was introduced in 2018 with the main focus on improving the video quality, providing the videos in a web browser-supported format, and reducing the power consumption. Even though model 3.0 looks visually similar to model 2.0, it was actually completely redesigned, including the microprocessor, and the software was also completely rewritten.

The cameras of model 2.0 were replaced by similar CCTV cameras that produced 720p video at 30 fps, already encoded in H.264 format. This is a well-established multimedia format, typically distributed inside MP4 media files. The new software has enabled storing activity-triggered videos and at the same time live streaming the video to an arbitrary number of clients. Streaming was provided by a standard Real Time Streaming Protocol (RTSP) server, allowing to play the stream by standard video players with RTSP support, e.g. VLC. Thanks to a restreamer software running on the university server, the stream was available via the Internet to the public without limitation.

The power consumption of the computer unit was reduced by choosing a modern, power-saving microprocessor, to 1.5 Watts. Anyway, the overall consumption was mainly influenced by the cameras, that had to be always recording to achieve fast trigger speed. As a result, we reached a negative trigger delay, effectively producing videos that started

Num. of cameras	0	1		2	
IR light state	N/A	Off	On	Off	On
Consumption [Watts]	**1.5**	**2.8**	**3.4**	**4.1**	**5.4**

Table 5.1: Model 3.0 power consumptions with respect to the number of cameras and infrared light state (switched on/off).

a few seconds before the activity but for the cost of higher power consumption. Based on the number of cameras and whether the IR lighting was lit on, the consumption varied from 2.8 to 5.4 Watts (see Table 5.1).

While model 1.0 was designed solely for battery-powered, offline operation, and model 2.0 focused on mains-powered, online operation, model 3.0 was designed to support all possible combinations of powering and connectivity modes. Powering options were defined by hardware configuration, being equipped either by a PoE adapter to transform the power from mains, or by PoE injector to simply inject the power from battery. Both online and offline connectivity options were enabled by software at once.

To reduce system costs, the temperature and light sensors of models 1.0 and 2.0 were not used for model 3.0. Instead, environmental sensors, including temperature, light, humidity, pressure and magnetic field sensor, were integrated on the board of IR light activity detector. Anyway, that did not prove to be a good choice in practice, as the sensors were covered by a wooden board, effectively measuring the conditions of the wooden box rather than outside conditions. For that reason, a new sensor board was developed in 2019 (not yet applied). Thanks to high extensibility of model 3.0 via unused ports and extension slots, the new board can be easily applied to the already installed SNBoxes.

5.4 University Server

Our university server `ptacionline.czu.cz` formed a central point of the project Birds Online / Ptáci Online that was organized at the Czech University of Life Sciences Prague. Its key feature was the operation of the OpenVPN server, allowing to connect all model 2.0 and 3.0 SNBoxes to a single Virtual Private Network (VPN). That enabled bidirectional communication between university server and each SNBox, required for the main services – data submission, live streaming, remote diagnostics and maintenance. Additionally, the university server also ran a webserver, presenting all recorded data and live streams to the public for free. The webserver was accessible at addresses `www.ptacionline.cz` and `www.birdsonline.com`, both offering Czech and English language mutations.

Two versions of the server were operated consecutively. The first version was launched in April 2016 and was used for two years. Due to the growth of the project, the server was further hard to maintain, so a second version was developed and launched in April 2018. Details on the second version of the university server and its functionality were presented in **Kubizňák et al. (2019)**.

Chapter 6

Proof of Concept

In course of the nesting seasons 2014-2019, we gradually manufactured and applied 56 SNBoxes to prove their suitability for research and educational purposes.

6.1 Model 1.0

Four pieces of model 1.0 SNBoxes were manufactured and first applied in the nesting season 2014 (see **Zárybnická, Kubizňák, et al. 2016**). Over that season, the SNBoxes were used sequentially for eight nestings of Tengmalm's owl, resulting in 3382 owl video events recorded over 309 recording days. The system helped us to identify 12 types of male and female parental activities and their timing, the diet composition and frequency of prey delivery, the manner of prey storage, the light intensity at the time of each parental activity, the temperature inside the clutch and outside the box and the duration of nestling period of each young (for details, see **Zárybnická, Kubizňák, et al. 2016**).

All model 1.0 SNBoxes have been operating since 2014. We have collected 16,834 video records on nesting of 48 owl pairs in the Ore Mountains in the period of 2014-2017, most of them unpublished yet. The potential of the collected data has been demonstrated in **Šindelář, Kubizňák, and Zárybnická (2015)** on research on sequential polyandry in female Tengmalm's owl during a poor rodent year, performed in 2014. Since diet structure may be undervalued using pellet analysis method (Zárybnická, Riegert, and Šťastný 2011), we used SNBox for determination of prey delivered to owl nests. Videos taken by the cameras enabled us to determine delivered prey at least to the family or genus level. It further allowed us to determine female and male parental care, i.e. the presence of parents on the nest and prey delivery rate by male and female parents. Adult owls were marked by chip rings. A camera system together with a chip reader device allowed us to record the arrival and departure of individual parents to the nest box, feeding frequency and species composition of prey delivered to the nests. Despite our expectation that sequential polyandry is conditioned by food abundance, we recorded one case of such behaviour. We documented the number and the structure of prey deliveries in both nests – 265 prey items (birds 44.1 %, shrews 28.3 %, voles 23.8 %; see **Šindelář, Kubizňák, and Zárybnická 2015**) within 52 recording days in the first nest, and 43 prey items (shrews 48.8 %, voles 30.2 %, birds 11.6 %; see **Šindelář, Kubizňák, and Zárybnická 2015**) within 13 recording days in the second nest. Videos taken by the SNBox camera system enabled the identification of prey delivered by owl parents as mammals (to the genus or species level) or birds. Only 2.3 % (n = 7 items) of all delivered prey were not determined.

6.2 Model 2.0

We installed and tested the first set of 22 model 2.0 SNBoxes in the Czech Republic in 2016, to show that this approach has potential to be an effective tool of Citizen Science and is applicable over large geographic areas. Because the price of an SNBox was quite high for civil applicants ($560 without services), we financed all SNBoxes through our own grant funding, allowing us to lend them to the public for free while collecting biological data for our research topics. We have incorporated the public (in particular schools) into the nest box installation and in providing the power and Internet connection, while we have provided them with live streaming and video recordings of birds nesting. We extended the number of SNBoxes in total to 33 in 2017, two of them being installed in Poland, the rest in the Czech Republic.

Model 2.0 SNBoxes have been working without great trouble since 2016 and continue to work to date. During the first nine-month period in 2016, we remotely collected more than 140,000 video recordings and 2 TB of data from 22 nest boxes, and almost 19,000 visitors viewed our websites. By August 2019, 33 nest boxes recorded over 660,000 videos. We have incorporated more than two dozens of university students into the video data analyses in terms of their bachelor and diploma theses, and each student analysed 7,000 video recordings (each 30 s long) in approximately one month, i.e. we processed about 100,000 videos so far. We gained comprehensive information on bird behaviour, including the timing of daily activities and breeding, incubation behaviour, provisioning rates, feeding and begging behaviours, mortality patterns, and fledgeling success. We also determined the structure of food delivered by bird parents to their nestlings. Common starlings delivered more and larger prey items at once, including crane fly, moths, owlet moths and even adults and larvae of dragonflies, while great tits brought separate smaller prey items, usually the larva of different unidentified small insects (Insecta: *Pterygota*). This finding is progressive regarding a non-invasive method of camera monitoring compared to other more invasive methods, e.g. Moreby and Stoate (2000) and Michalski et al. (2011).

6.3 Model 3.0

We manufactured 20 model 3.0 SNBoxes in 2018. 18 of them were installed in urban areas of the Czech Republic right before the start of the nesting season of 2018, and one device was installed in October 2018 in the U.S. (see below). By August 2019, these 19 devices recorded over 190,000 short video recordings (each record usually 30 s in duration). Model 3.0 devices, compared to model 2.0, recorded higher-quality video concerning the frame rate (30 fps vs 4-8 fps, see Chapters 5.2 and 5.3). On the other hand, the video was darker due to the camera factory calibration (for details, see **Kubizňák et al. 2019**).

One model 3.0 SNBox was installed at Cornell University, Ithaca, United States, by the end of October 2018. Shortly afterwards the first exploration visits of the northern flying squirrels (*Glaucomys sabrinus*) started. They chose the SNBox for night huddle during winter months - from December 2018 till March 2019. On some occasions, between five to seven individuals stayed overnight. At the end of April 2019, a couple of the American red squirrel (*Tamiasciurus hudsonicus*) built a nest during a few days and laid five young afterwards. As the offspring grew and explored the SNBox interior and its equipment, they managed to chew up the cable of the top camera and disabled its function while the entrance camera stayed still fully functional. After they left the SNBox, the camera captured casual visitors such as house wren (*Troglodytes aedon*) and common starling (*Sturnus vulgaris*). The SNBox has been operating for three quarters of the year and made almost 8000 video recordings so far.

All installed model 2.0 and model 3.0 SNBoxes were operated online. We have shared the live stream and video recordings on websites, which allowed the public to watch animal life live or retrospectively, and it has become attractive and popular among users. In particular, teachers used live streaming and video recordings in schools to directly introduce bird life during lessons on biology and the environment. As a result, schoolchildren have created pictures and bird stories while increasing their biological knowledge (Zárybnická, Sklenicka, and Tryjanowski 2017). They have substituted anonymous textbook information with a personal relationship to a place and with particular bird individuals who breed in their school garden. Moreover, older students have used the video recordings to produce videos on bird nesting, while students in the higher classes of vocational training schools have made wooden boxes with built-in structures for technical devices (Zárybnická, Sklenicka, and Tryjanowski 2017). I suggest this approach is highly effective in increasing biological knowledge and environmental awareness of the public and students across educational levels. In 2017, we have also installed model 2.0 SNBoxes in hospitals and senior housing documenting that the use of high-quality technologies in Citizen Science projects can attract wide audiences to participate in these projects, leading to the growth of public education effects across society. As a result, this approach can help with standardizing and optimizing Citizen Science in the future for which it is called (Heigl and Dörler 2017).

6.4 University Server

From April 2016 to April 2018, the first university server collected around 470,000 video records (6.6 TB) from 33 model 2.0 SNBoxes. Since April 2018, the second university server collected over 850,000 video records (11 TB), submitted by 33 model 2.0 (660,000 videos; on average 20,000 per device) and 19 model 3.0 (190,000; on average 10,000 per device) SNBoxes. The disproportion is caused by having installed the model 3.0 SNBoxes in 2018 too late, hence the nest boxes were not much used by birds during that season (see the results in **Kubizňák et al. 2019**).

In total, we collected around 1,320,000 video records. Raw data (video records and metadata) submitted by all SNBoxes by August 2019 occupied around 18 TB of drive space. From these raw data, presentation data were extracted automatically - the model 2.0 videos were converted to the MP4 format (see Chapter 5.2) while the model 3.0 videos were simply copied. The data collected by the first server are no more publicly available. All presentation data extracted by the second server (3.8 TB by August 2019; see Fig. 6.1) are publicly accessible on the website.

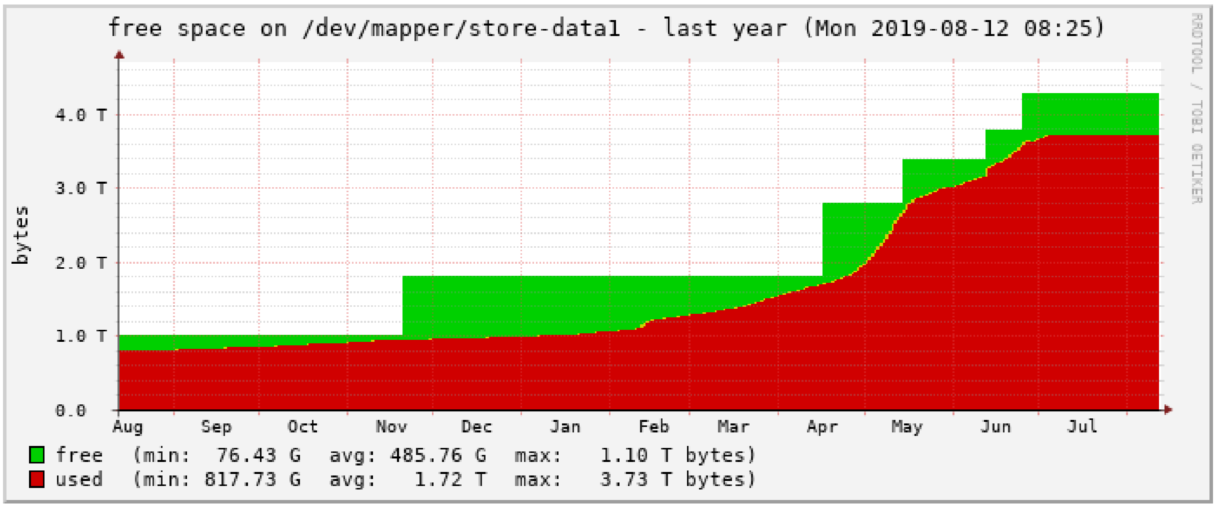


Figure 6.1: The size of video data presented by the second version of the university server from August 2018 to August 2019. The rapid growth of the data size (red) from March to June 2019 corresponds to the nesting season. The server storage capacity (green) required to be increased several times.

The website was visited frequently. Involving both server versions, we encountered around 460,000 page views in 60,000 visits made by 38,000 unique users from 107 countries (78.2 % of Czech visitors) by August 2019.

Chapter 7

Discussion

Results from the six nesting seasons show our system strengths and weaknesses. Below I discuss its potential and the challenges that yet need to be resolved.

7.1 Big data processing is challenging

SNBox is a powerful tool for collecting high amounts of potentially valuable scientific data. To turn these data into research results, they need to be processed, which can be really challenging.

During the first year of the model 2.0 operation, i.e. from April to December 2016, 22 SNBoxes recorded over 144,000 videos occupying over 2 TB of our server data storage. As we sequentially increased the number of model 2.0 and 3.0 SNBoxes to the current 52 devices installed, the amount of submitted data grew proportionally. By August 2019, we collected over 1.3 million videos occupying around 18 TB of data storage (raw data excluding backups and presentation data). By incorporating over two dozens of university students into the video data analyses, where each student analysed 7,000 video recordings, we processed about 100,000 videos. Analysis of 7,000 video recordings is a highly time-consuming activity – it takes approximately one month of intensive work. In this light, it turns obvious that finding a scalable approach for data processing is inevitable for mass application of SNBoxes. This is where the power of Citizen Science could be leveraged to fully employ crowdsourcing mechanisms (Doan, Ramakrishnan, and Halevy 2011). In particular, web users could be invited to classify the content of the video records they recently watched. This could be done as a future extension of our website or by using a well-established crowdsourcing platform, for instance, Amazon's Mechanical Turk (Buhrmester, Kwang, and Gosling 2011), Prolific Academic (Peer et al. 2017), or the scientifically focused Zooniverse (Cox et al. 2015).

Furthermore, big data acquisition brings up the problem of its storage and management. It could be solved using a general-purpose cloud service, e.g. Microsoft Azure or Amazon Drive. Additionally, a global infrastructure, like eMammal (Forrester et al. 2017), would be profitable for global application to facilitate building partnerships among existing projects and increase local support for new camera projects that can be more explicitly linked to regional and global camera networks (Steenweg et al. 2017).

7.2 Using machine learning for the extraction of biological information

Although crowdsourcing mechanisms could be a solution for some individual projects, they will always remain constrained by the number of volunteers willing to participate and their experience. For a truly scalable approach, the work needs to be done fully automatically.

Our data could potentially be subject to a wide range of analyses. The incorporation of computer vision algorithms for the automatic classification of the video content, e.g. Yu et al. (2013), Egnor and Branson (2016), and Nasirahmadi, Edwards, and Sturm (2017), might replace some manual evaluation tasks in the future. For example, well-established algorithms exist that could be used for arrival/departure detection or egg and nestling counting. Following the terminology from Chapter 3.7, arrival/departure detection is a description task. I suggest this can be resolved by evaluation of a motion vector, calculated by a motion tracking algorithm, applied on the portion of the video with a bird entering/leaving the nest box (i.e. first few seconds of the record).

Egg and nestling counting is a counting task. This can be relatively easy given that the counted objects are well visible and recognizable. For example, Pandit et al. (2015) implemented a very reliable (97 %) silkworm egg-counting algorithm based on simple morphological operations. That was allowed by laboratory measurements with well-defined conditions. Our records are characterized by low contrast and high noise, occlusion and clutter. Using an appropriate feature detector, which is more robust to these flaws, may be inevitable. For example, using a blob detector may be suitable for eggs detection. This should be quite easy for night records when the eggs reflect the IR light and are well-visible even if covered by the nest material. In daytime records, some eggs may be almost invisible which will probably limit the counting accuracy. Nestling counting would require to find a reliable detector of e.g. heads or beaks but the reliability will be always limited by occlusion.

Tasks from the identity group, like animal re-identification (Schneider et al. 2019), required for tracking and understanding the individuals' behaviour, or detailed food classification, could be based on deep learning mechanisms. As machine learning is a rapidly growing and evolving field, I anticipate that it will make a real breakthrough in future ecological researches but the technology needs to progress to the point where the deep learning algorithms can be used as a black box, without the need to understand the internals. Ultimately, the artificial intelligence may be once capable to resolve all the tasks by fully interpreting the scene into a dynamic model of the whole nest box and its content that could be further evaluated.

7.3 Possible future improvements to the system

Development of electronic devices is never finished. Although model 3.0 is definitely well applicable in the field, I identify many topics for potential future improvements.

7.3.1 Cameras

The most important component of any video surveillance system is its camera. We have posed high requirements on this component – high light sensitivity for operation in dark conditions, operation during nighttime (monochrome) and daytime (colour), sufficiently high video quality (i.e. resolution and frame rate) for comfortable watching, low cost, and small size for embedding in the size-limited nest box area. We have chosen commercial CCTV cameras with USB interface, as they offered relatively good video and audio quality while providing the USB Video Class (UVC) interface, i.e. they were easy to use and control from the Linux Operating System (OS), and they featured automatic video settings adjustment and day/night switching.

Anyway, while we originally appreciated the automatic behaviour of the cameras, we found it to be limiting later. It was not possible to control the conditions of day/night switching, resulting in two issues. First, the cameras switched from day mode to night mode when there was already too much darkness, producing a very dark video for a significant portion of daytime. Second, the switching was unstable, i.e. it often happened that the camera started to fluctuate between the day and night mode, resulting in acoustic disruptions (the operation involves a mechanical movement of the IR-cut filter, making a relatively loud click). Additionally, to bring enough light to the camera chip, we used a lens with relatively high numerical aperture, leading to a low depth of field when focused to short distances (about 15 cm in our case). As a result, the video was mostly unsharp, and the sharpness changed in the course of the nesting as the birds grew. Finally, the cameras were not optimized for quick startup. To achieve high trigger speed, the cameras had to be always powered on and, in case of model 3.0, even permanently recording, resulting in high power consumption.

Future system improvements will be hence mostly concentrated around cameras replacement. Instead of using an automatic USB camera, we could look for a camera with Camera Serial Interface (CSI) and electronically focusable lens. The advantage would be a higher control over the camera functionality, sharp image, much faster startup and lower power consumption (significantly lower if we consider instant recording without buffering). The disadvantage would be more complicated software and the need for yet another hardware redesign (a microprocessor with CSI interface and multimedia codecs accelerator would be required).

7.3.2 System Powering

Aforementioned camera replacement and hardware redesign would allow for significantly longer performance on battery. While the current solution can be operated with a heavy 12 V traction battery from few days to one or two weeks, based on the battery capacity, settings and birds behaviour, the device life could be extended to one month and more, which would allow for researches in detached, hardly accessible areas. This is the field where current camera traps beat our solution.

Another approach for extending battery life would be equipping the device with solar cells (for details, see discussion in **Kubizňák et al. 2019**). This would ideally allow for continuous, maintenance-free operation. It is surely possible to do so without aforementioned hardware redesign, but it would require larger solar cells, which would be more expensive, more distractive to the animals and more attractive to human interference, increasing risk of theft or vandalism. Hence I suggest solar cells are better reasoned together with the hardware redesign.

7.3.3 Connectivity

Having a self-powering device, it is highly reasonable to extend the system connectivity by a Global System for Mobile Communications (GSM) modem, realizing the permanent connection of the device to the Internet, independently of nearby wired/wireless hotspots (for details, see discussion in **Kubizňák et al. 2019**). This would effectively turn the SNBox to a real IoT device that could operate unattended for long time periods at nearly any place in the world. The only limiting factors would be the presence of sufficiently fast mobile network and enough sunlight for battery recharging. Additionally, the problem with the insufficient mobile network signal could be overcome by satellite communication (Zheng et al. 2018).

Talking about IoT, one might think about incorporating some of the various networks particularly designed for IoT, e.g. LoRaWAN or Sigfox. These networks belong to the Low-Power Wide Area Network (LP-WAN) technologies (Ikpehai et al. 2019). As the name suggests, they are designated for low-power devices (typically some sensors), transmitting low data volumes, hence not being suitable for multimedia transmissions.

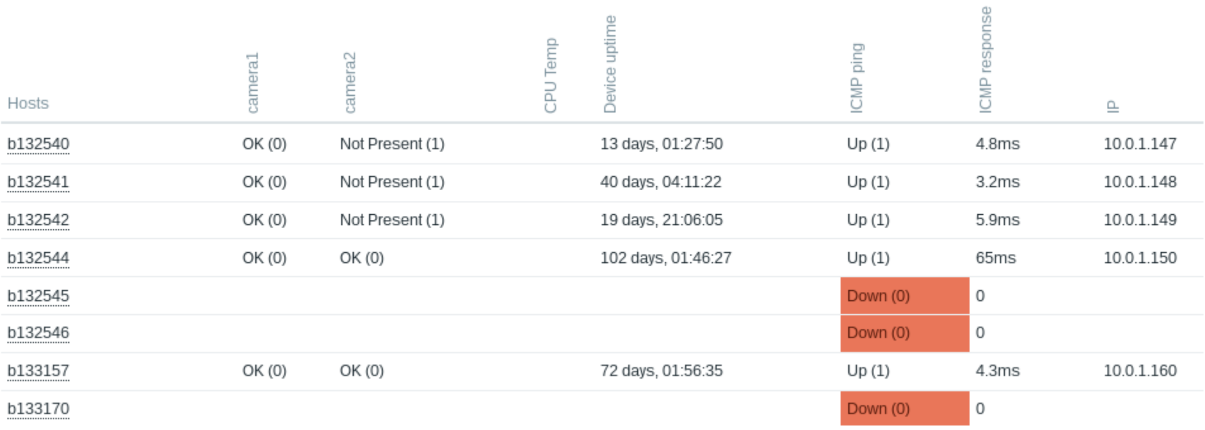
7.3.4 Extensions

The computer unit of model 3.0 has been designed to allow for various future extensions. The range of sensors can be extended or modified according to research objectives, by incorporating sensors that measure environmental features such as precipitation, wind, NOx, CO2, CH4, LPG, and dust. In addition to environmental measurements, other sources of ancillary data can be added. For example, RFID reader, that was a standard part of model 1.0 (see **Zárybnická, Kubizňák, et al. 2016**), and optional part of model 2.0, could be easily reintroduced to model 3.0 as an extension card (for details, see discussion in **Kubizňák et al. 2019**). We have also designed and developed prototype of a scale to weigh nest contents and an infrared thermometer for contactless measurement of temperature of the clutch and nesting material (Šálek and Zárybnická 2015), as well as the external speaker connected to the computer unit in order to conduct acoustic experiments (Injaian, Taff, and Patricelli 2018). None of these devices has been tested though, and hence they represent only examples of potential future development.

7.3.5 Software Improvements

The core system functionality is complete, the system performs stably, and there is a range of advanced features that can be used. Anyway, the system is not easy to understand and its configuration is complicated. The next steps in software development should be to simplify the system use while not reducing its functionality.

All SNBox models produce application logs that can be used for troubleshooting of various system failures or unexpected behaviour. Anyway, these logs require expert knowledge of the system software, so it is effectively only me who understands them. For that reason, a universal diagnostic mechanism based on a Simple Network Management Protocol (SNMP) was introduced in model 3.0. Each model 3.0 SNBox runs an SNMP server, through which it publishes its diagnostics data. The university server runs a Zabbix software, which is basically an SNMP client, which periodically fetches these data, and a graphical web frontend (see Fig. 7.1). At the moment, the data are limited to a few values, e.g. state of both cameras (OK / Not Present / Error). This could be extended to present much more detailed insight, e.g. state of all attached peripherals, configuration, an overview of collected data, etc. Additionally, the SNMP protocol is not only designed for displaying read-only data but could be as well used to alter read-write data, hence allowing to be turned to a control and configuration interface.



Hosts	camera1	camera2	CPU Temp	Device uptime	ICMP ping	ICMP response	IP
b132540	OK (0)	Not Present (1)		13 days, 01:27:50	Up (1)	4.8ms	10.0.1.147
b132541	OK (0)	Not Present (1)		40 days, 04:11:22	Up (1)	3.2ms	10.0.1.148
b132542	OK (0)	Not Present (1)		19 days, 21:06:05	Up (1)	5.9ms	10.0.1.149
b132544	OK (0)	OK (0)		102 days, 01:46:27	Up (1)	65ms	10.0.1.150
b132545					Down (0)	0	
b132546					Down (0)	0	
b133157	OK (0)	OK (0)		72 days, 01:56:35	Up (1)	4.3ms	10.0.1.160
b133170					Down (0)	0	

Figure 7.1: Portion of a Zabbix screen in a web browser. Each row shows diagnostics data on a single SNBox device.

System configuration is defined by three configuration files – one for overall configuration and two for the cameras, one for each. At the moment, the configuration files could be either modified directly using a Secure Shell (SSH) connection, which is highly error-prone, or by uploading the configuration file over the SNBox webserver. The latter approach adds a validation check, which does not allow to apply an invalid configuration, but in principle, it is not easier – user still needs to understand the configuration file well and edit it properly to achieve the required behaviour. Ideally, a user-friendly interactive configuration interface should be implemented in the SNBox webserver. Such a well-designed interface would allow to reduce the learning curve to the minimum and prevent the user from applying invalid and undesired configurations, while not limiting the system functionality.

The live stream from model 3.0 can be played by any media player capable of RTSP stream playback, e.g. VLC. This allows the users inside the LAN to watch the stream on any desktop computer, assuming they know the SNBox Internet Protocol (IP) address and are able to enter it to the player in the correct format. Anyway, it is not possible to easily play the stream on modern multimedia devices like Smart TVs. That could be solved by installing a Digital Living Network Alliance (DLNA) server on the SNBox. DLNA server is used for advertising available multimedia files (video, pictures, music) to any DLNA client in the network. That allows Smart TVs and other multimedia devices to lookup for all multimedia providers available in the network, show the list of content and start playback of selected media. As a result, users would be able to play the live stream and even all captured videos on any modern multimedia device like a Smart TV or a tablet with installed DLNA client, even without knowing SNBox IP address.

7.4 The system and its potential for commercialization

While model 1.0 was developed strictly as a purpose-designed system, the later models were designed with commercialization in mind. For that reason, system use was simplified, capabilities were extended and the overall cost was significantly reduced.

Two pilot orders were processed and dispatched in March 2019. First, four SNBoxes were sold to Česká společnost ornitologická (Czech Society for Ornithology), Czech Republic, for monitoring of little owl (*Athene noctua*). All SNBoxes were equipped by two cameras and prepared for both battery-powered and mains-powered configuration. Three of these devices were installed for the season 2019, and two of them got inhabited. Some recorded videos were published online at Česká společnost ornitologická (2019). Second, ten SNBoxes were sold to University of Venda, Thohoyandou, South Africa, for research of barn owl (*Tyto alba*). All these devices were equipped by one camera and prepared for battery-powered operation. They were not installed to date of writing this thesis due to researchers' schedule, though.

The pilot orders confirmed that model 3.0 is a mature surveillance system that is useful for other researchers, and that can be operated without our permanent supervision. On the other hand, it has shown there are still some weaknesses. Mainly, the system is not easy to setup. System configuration realized via a set of configuration files is not suitable for biologists. They are usually not familiar with the networking setup, neither. Detailed user manual, that would allow them to install and operate the system, maybe with some assistance of their IT specialists, is a must. It has not been completed yet, though. And to allow for commercial online-operated devices, the software running on the university server would need to be generalized, documented and packaged to enable installation on the customer's server or a cloud.

To evaluate the potential for commercialization, we need to consider the main types of potential customers: (1) individuals, e.g. amateur ornithologists, (2) educational institutions, e.g. schools or eco centres, and (3) research institutions, e.g. universities or biological institutes.

The first group, i.e. individuals, is generally cost-sensitive and does not much appreciate advanced features like environmental sensors. They are mostly interested in live streaming which can be realized by any IP camera for a much lower cost. Suitable IP cameras are on the Czech market available for less than \$100 (e.g. LAN-SHOP.cz n.d.). Complete nest boxes with embedded IP cameras are offered by BudCam.cz (n.d.) for \$200-\$300. I suggest this choice is more suitable for laic individuals than our SNBoxes.

The second group, i.e. educational institutions, is less cost-sensitive. They appreciate both live streaming and activity-triggered recording, so they can focus on bird activities during lessons. The institutions are typically not interested in custom configurations, they want to use the device “as-is”. That involves that retrieval of the activity-triggered recordings needs to be extremely easy. One option would be using a cloud service to run our server software. Another option would be an implementation of the DLNA server running on the SNBoxes. Having this issue solved, educational institutions could form a significant number of orders.

The third group, i.e. research institutions, is driven by the research objectives and is not that much limited by financial conditions. They require extended functionality, high configurability, and they generally want to have the recorded data fully under their control. For offline-operated devices, there are no critical issues, and the pilot orders show that the system is ready to be offered, with the remark that the user manual needs to be finished. For online-operated devices, there is a high potential for use by research institutions but the server software needs to be made available to the customers which can be a challenging task.

The above analysis shows there is a relatively high chance of providing our system to other institutions on a commercial basis. However, it also shows that more work needs to be done to meet all the requirements. Taking into account the high costs of development works and relatively low profit from selling price, it is questionable whether commercialization makes sense. In the other case, the potential of the system as a tool for research and education would be thrown away. An alternative solution could then be to turn the system into an open-source platform.

Open-source software is a type of computer software in which source code is released under a license in which the copyright holder grants users the rights to study, change, and distribute the software to anyone and for any purpose (see Wikipedia 2019). It is a well-established phenomenon, with a worldwide base of software developers, forming a so-called community that works on the open-source software development collaboratively. One of the most-known open-source software is the Linux kernel and the whole world around Linux distributions. After all, the SNBox software is also mostly just a compilation of open-source Linux software, with a relatively small part of the application layer being proprietary (closed-source). It would not be difficult to publish all these portions of code and equip them by an open-source license. Any software developer interested in the project would then be able to adjust and improve the code, which might move the system forward without the need for further investments. On the other hand, opening the source code certainly does not guarantee that someone would continue in the works. Most probably it would still be necessary to manage the project and actively encourage other developers to make it improve. Otherwise, the development might be abandoned, which is the destiny of a high portion of open-source software. For that reason, I am not currently planning to open-source the system software.

The open-source term is not limited to software, though. There are also open-source hardware initiatives, like BeagleBoard.org Foundation (n.d.), that try to bring the same collaborative principles to the world of hardware design. With open hardware, all hardware description files are published, granting everyone the rights to adjust the hardware and manufacture it in an arbitrary factory. Releasing our system hardware under an open-source license could theoretically extend its use to a worldwide scope. On the other hand, it could as well lead to a slow end of the project for the similar reason as when open-sourcing the software, i.e. there might be no company willing to further develop and manufacture the hardware due to insufficient margin. For that reason, I do not currently consider open-sourcing our system hardware as appropriate.

7.5 The system and its potential for biological and educational purposes

Our system has been primarily developed as a tool for biological research. It is suitable for collecting comprehensive information on nest box-nesting bird behaviour, including the timing of daily activities and breeding, incubation behaviour, provisioning rates, feeding and begging behaviours, diet structure, mortality patterns, and fledgeling success. We have presented some biological results, including previously undocumented behaviour, on Tengmalm's owl (*Aegolius funereus*) in **Zárybnická, Kubizňák, et al. (2016)**, and we published research on Tengmalm's owl female polyandry, enabled by using SNBoxes, in **Šindelář, Kubizňák, and Zárybnická (2015)**. We further dispose of a high amount of unpublished data on Tengmalm's owl, collected by model 1.0 SNBoxes. Using model 2.0 and 3.0 SNBoxes, we have collected an overwhelming amount of biological data on songbirds, mainly great tits (*Parus major*), common starlings (*Sturnus vulgaris*) and house sparrows (*Passer domesticus*). Since only a relatively small portion of these data has been processed so far, no biological results have been published yet. Model 3.0, being intended for all combinations of online/offline connectivity and mains/battery powering, has great potential for biological research in urban, as well as detached locations. Besides our own results, this is also demonstrated by two recent pilot commercial orders, aiming to use the system on owls monitoring in the Czech Republic and South Africa.

The educational opportunities provided by our system have been outlined in **Kubizňák et al. (2019)**. The educational effect was achieved first by designing our effort as a Citizen Science project, and second by installing SNBoxes in public institutions, mainly schools. That allowed teachers to use live streaming and video recordings to directly introduce bird life during lessons on biology and the environment. They have substituted anonymous textbook information with a personal relationship to a place and with particular bird individuals who breed in their school garden. This was in detail described in Zárybnická, Sklenicka, and Tryjanowski (2017).

Current system design limits its use to study animals nesting in or visiting artificial nest boxes. That involves a portion of birds, but also some mammals (e.g. bats, squirrels), reptiles and insects. After performing some adjustments, the system could be used virtually at any place in the world with reasonable climate conditions. Anyway, the willingness of animals to use artificial boxes can geographically vary based on local conditions. For example, there is a sufficient number of natural cavities in Ithaca, United States, which reduces the chance that a bird uses the artificial box for nesting. Instead, our SNBox got inhabited by squirrels, which was interesting from the methodological point of view, but it actually didn't much promote our system because squirrels are abundant there and are generally considered pests.

Chapter 8

Conclusion

Over the past seven years I have been working on development, application and evaluation of an automatic embedded system for cavity-dwelling bird surveillance, called the Smart Nest Box. I have gradually developed three models of the system.

The first model was designed as a single-purpose system for monitoring of Tengmalm's owl (*Aegolius funereus*). Application of four devices in the Ore Mountains, Czech Republic, proved its scientific benefits. However, this battery-powered, offline-operated system has shown to be demanding on regular maintenance.

For this reason, the second and third models were designed as the Internet of Things systems allowing for maintenance-free performance thanks to powering from mains and online operation. In total 52 devices of the second and third model were manufactured and installed at third-party locations, 49 of them in the Czech Republic, two in Poland and one in the United States. We employed mechanisms of Citizen Science by providing the applicants with a tool for observing birds nesting at their premises while they provided electricity and the Internet connection, allowing to autonomously collect and submit valuable scientific data to our server. The educational effect was further enhanced by installing most of the devices at schoolyards, allowing the teachers to play the live stream and recorded videos during lessons on biology and the environment.

By combining the power of the Internet of Things and Citizen Science, our system showed enormous potential for collecting overwhelming amounts of biological data useful for scientific research on animals nesting in cavities. This has been confirmed by receiving two pilot orders on 14 devices in total. The next step is to establish a robust, scalable mechanism for reliable analysis of all received data, which is challenging. To some extent, this could be realized by further leveraging capacities of Citizen Science, but generally, the only feasible solution seems to depend upon computer vision and machine learning to process the data fully automatically.

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