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Designing network-connected systems for ecological research and education

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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.

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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.

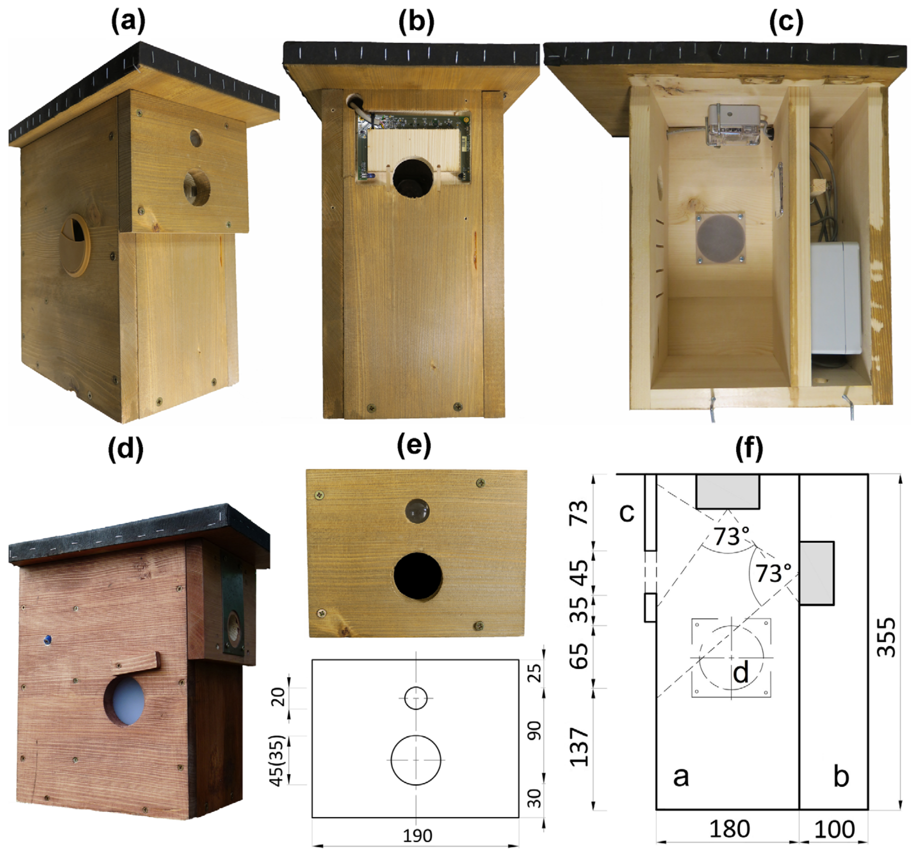

Fig. 1. The design of the model 3.0 smart nest box (SNBox) and its individual parts. (a) The completed SNBox. (b) A front view of the SNBox exposing the IR light activity detector board upon which environmental sensors were also located. (c) The inner SNBox space containing a nesting area with one or 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

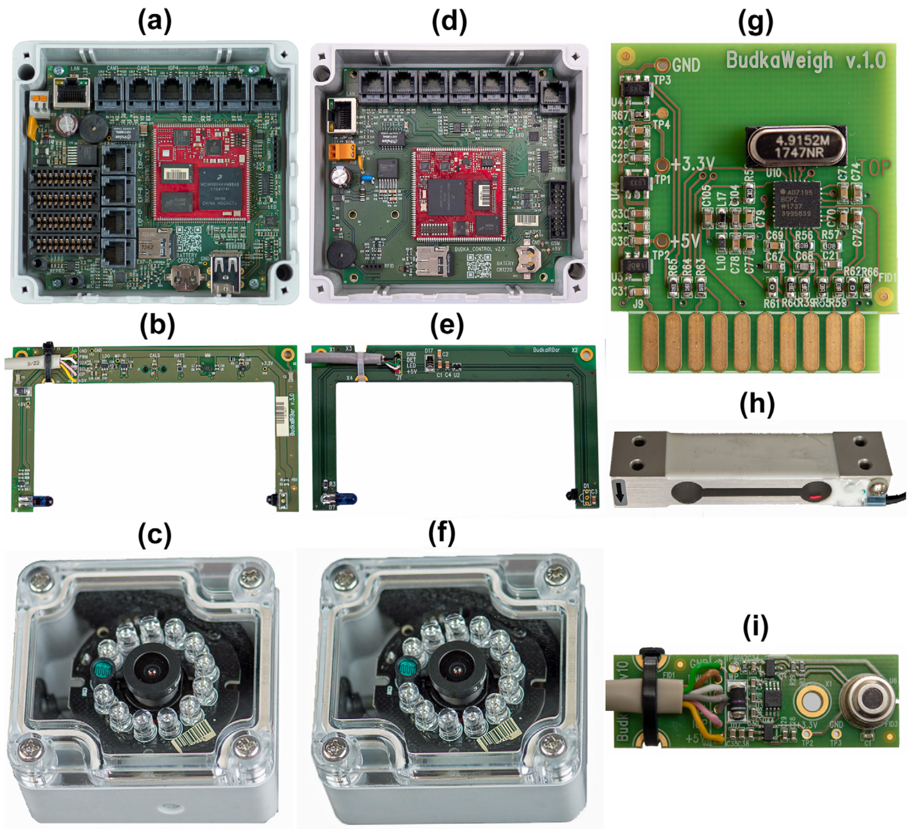

Fig. 2. Electronic components and peripherals of the model 2.0 and 3.0 SNBoxes. The custom-designed computer unit in the opened plastic housing of the models (a) 3.0 and (d) 2.0. The custom-designed IR light activity detector of the models (b) 3.0 and (e) 2.0. The commercial camera of the models (c) 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

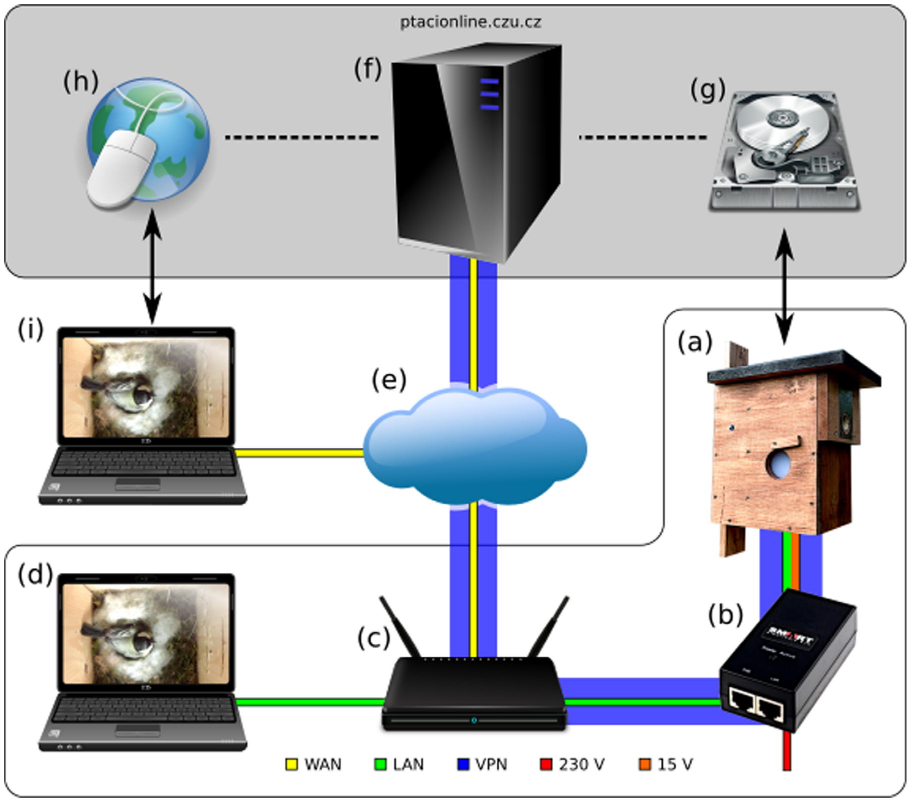

Fig. 3. A schematic of the networking infrastructure of the SNBox camera system (models 2.0 and 3.0). (a) The SNBox installed at the host locality. (b) PoE adapter. (c) Host's router, a central point of the local area network (LAN) and the gate to the wide area network (WAN). (d) Local user PC. (e) The 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,

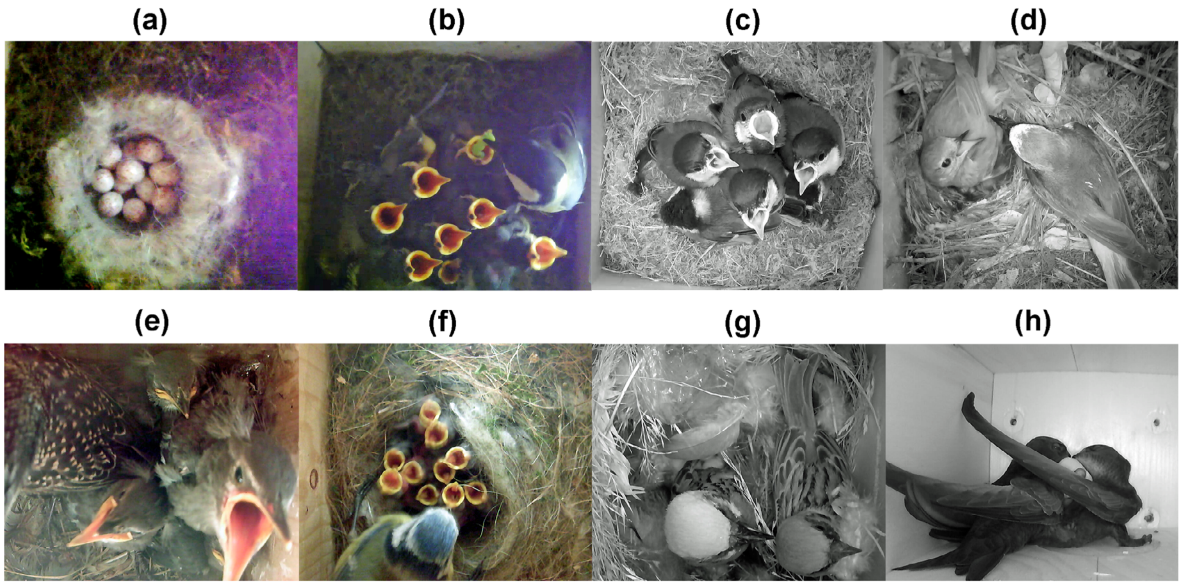

Fig. 5. Examples from videos recorded by the camera system of the SNBox: still image of (a) a clutch of great tit (*Parus major*) eggs, (b) a parent great tit feeding the nestlings, (c) great tit nestlings, and (d) an incubating female and male parent common redstart (*Phoenicurus phoenicurus*) recorded 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 live-stream 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

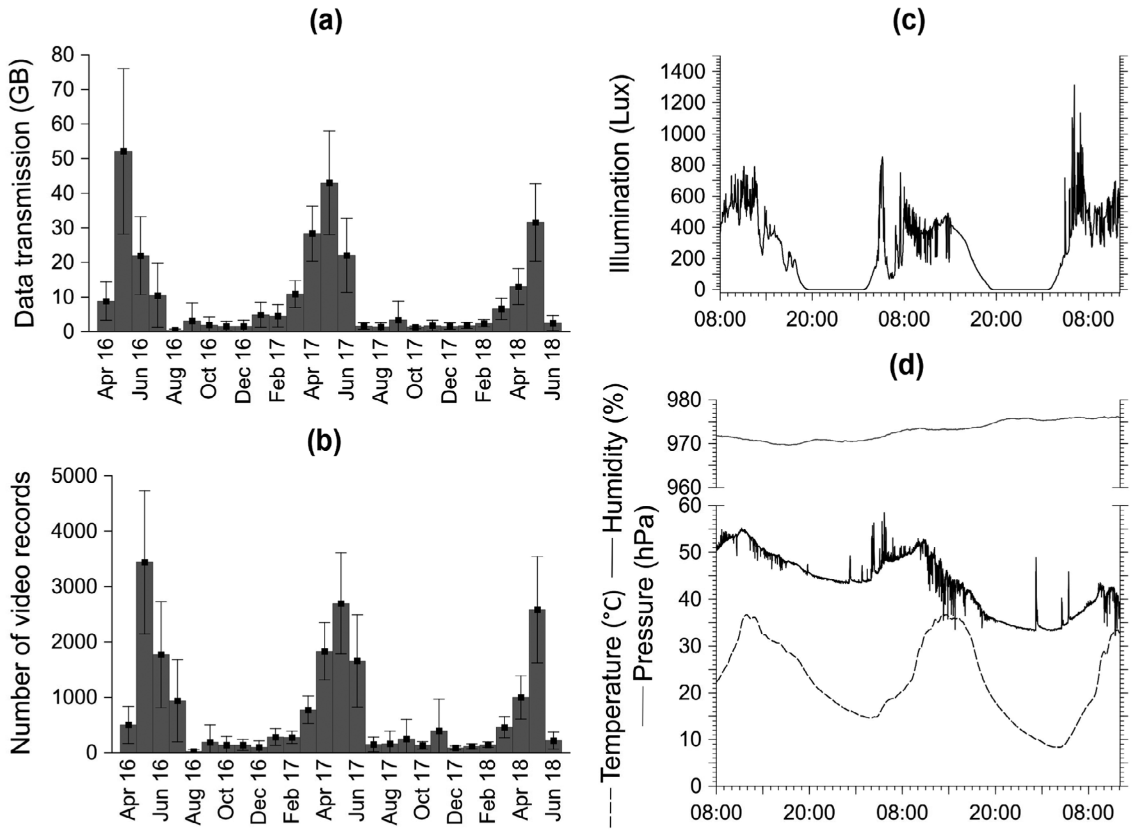

Fig. 6. Rates of data acquisition using SNBoxes and examples of data collected by environmental sensors embedded in the SNBox. (a) Mean monthly volume of data (GB) and (b) the number of video recordings transmitted from each SNBox (mean ± SD) to the university server between April 2016 and June 2018. 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 offbouts, 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.

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Supporting Information

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