Monitoring Technologies for Animal Welfare: a review of aspirations and deployments in zoos

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Abstract

Focusing on zoo environments, we conducted a literature review investigating the use of non-invasive technologies designed for monitoring the behaviour and welfare of animals. The research question asks: What technologies or monitoring methods have been able to capture information on behaviours and needs of animals in zoo, sanctuary, domestic or agricultural environments? From the initial literature review, we determined progressive zoos, research labs, institutions and companies and identified monitoring technologies developed to improve animal welfare. We then emailed out a concise survey to those zoos to gauge what monitoring technologies they were using and asked them to identify where systems and their deployment could be improved. We highlight advances and developments identified in the literature, to underline current and future monitoring needs of zoo environments. We contribute to the research field by mapping these sought-after changes against the most relevant identified monitoring technologies distinguished in the literature search

Keywords: Animal Welfare, Monitoring Technologies, Zoos.

1 Introduction

Routine monitoring of animals in captive settings is essential to provide insights into the quality of life of the animals and for maintaining and improving exacting standards of animal welfare in zoos. Monitoring technologies are useful for optimizing welfare strategies with non-invasive observation of animals. Advanced tracking and monitoring technologies are used for welfare considerations for livestock, captive, and wild animals. Monitoring the behaviour of animals in zoos promotes science-based decision making and future planning for best-case animal care solutions [1]. While one of the goals of this research is to find technological solutions to take labour intensive duties off zookeepers including smart data collection and analysis, the focus is the identification of non-invasive monitoring technologies to enhance animal welfare.

We identified progressive zoos, research labs, institutions and companies working with monitoring technologies to improve animal welfare [2]. We review literature on wearable and nonwearable monitoring technologies including camera traps, remote video camera systems (CCTV), additional technologies, software applications and digital tools for data collection, storage, sharing, and analysis. We include monitoring technologies from sanctuary, domestic and agricultural environments as these may also prove fit for purpose in zoo environments. We sent a questionnaire survey with five plain language questions to zoos identified as being concerned with animal welfare [2] to determine what monitoring technologies were already in use and what their future 'wish list' would be.

In structuring the article, we have placed the method section after the introduction and before the literature section. The method section, (section 2), details the literature review selection process to provide context for the 'literature reviewed' section (section 3) which forms the greater part of the of the paper. Section 4 covers zoo responses to the five-question survey on current use, perceived limitations, issues and wish lists for improving conditions and animal welfare. The discussion section outlines and maps these wish lists and more general requirements beside existing, or in-technology-development-solutions identified in the 'literature reviewed' section. The conclusion summarizes the findings and recommendations for the zoo scenarios that may be more broadly applicable.

2 Literature Review Method

We conducted the literature review using samples of keyword searches via google and google scholar (e.g., zoo monitoring, behaviour monitoring, monitoring, behaviour monitoring, behaviour remote) using the PICO process [3]. We found a variety of publications and resources that we include in this article.

P (population) – Captive/contained animals
I (intervention) – Technologies, Observations, Monitoring
C (comparison) - Zoo, Sanctuary, Agricultural, Domestic Environments
O (outcome) – Understanding Best Monitoring solutions for animal welfare

We included articles, conference publications, websites, reports, blogs as dissemination formats. We incorporated technologies used for animal welfare in domestic, farm, and wild animal settings in the search as these may also prove fit for purpose in zoo environments. Most of the analysed papers were published within the last ten years, even though we did not restrict the years within the search process.

3 Literature Reviewed

In this section we highlight the technologies covered in the literature review process that relate to potential use for zoo environments.

Monitoring the behaviour of animals in zoos can provide valuable insights into animal welfare and promote a process of science-based decision making in animal management [1]. Monitoring relates to (remote) monitoring of the animal behaviour, control, and studying the populations of wildlife (see Fig 1).

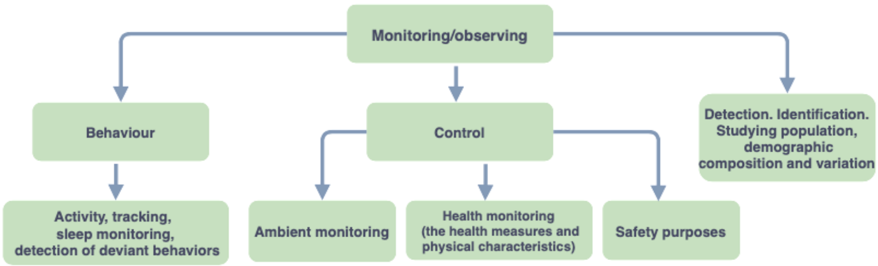

Fig 1. Reasons for Monitoring. Diagram by Aleksandra Novikova.

Behavioural monitoring is the scientific collection of animal behaviour data to understand 'normal' patterns of behaviour and identify changes in these patterns [4]. Used effectively, monitoring can indicate problems compromising animal well-being.

We identified non-invasive wearable and non-wearable technologies as tools for monitoring animal welfare and organised these technologies accordingly.

3.1 Wearable technologies

Advances in sensor technology (especially miniaturization) mean multiple wearable devices have been specifically designed or modified for animal use [5]. Devices include smart collars and cuffs using tracking, accelerometer sensors [6], pedometers and real-time health monitoring systems with antenna, relay routers, and base stations [7]. These are widely used in situ conservation and in agriculture. Non-invasive wearable technologies can be used as a primary or supportive tool, depending on the animal and their tolerance for 'attachments' on their body. For domestic and wild animals, wearable sensors are primarily used to detect and track the animal's movement. The technologies can provide insights into the behaviour and function of organisms in their natural environments, which might ordinarily be hostile to the observer, supporting determining animal's social relationships; and obtaining precise movement patterns.

Bio-logging and bio-telemetry monitor physiological, behavioural, or otherwise difficult to observe or unattainable environmental information [8]. Bio-logging technology records and stores information in an animal-borne device (archival logger), information is downloaded once the logger is retrieved, where bio-telemetry technology sends information to a receiver within the device [9]. Logger technologies are primarily used for monitoring and evaluating behaviour, spatial ecology, energetics, and physiology of free-living animals in their natural, harsh environments (e.g., polar regions, aquatic/marine environments), for rapidly moving or cryptic animals, and for those that undertake large-scale movements/migrations (e.g., birds, insects, marine mammals and fish) [9]. Lightweight geolocators or satellite transmitters [10] have enabled modelling of migratory routes and wintering areas for large and small birds, facilitating testing predictions on migration strategies. With light-weight radio transmitters even insects can be tracked for at least a part of their migratory journeys [10]. With environments that are hostile to the observer, bio-logging technology provides insights into the behaviour and function of Sea Mammals [8]. Combining these developments changes the capacity to conduct ecosystem-scale science and to improve the capacity of scientists to explore unanswered ecological questions [11]. We see bio-telemetry (radio telemetry, acoustic telemetry, satellite tracking), biologging (archival loggers), and hybrid technologies used for understanding the threats and causes of population decline and assessment of endangerment status of species [9].

A wireless activity monitoring system (Wireless Sensor Network (WSN)) would allow scientists to collect data and investigate behaviour without needing to chase and capture animals and offers a promising solution to monitor animal behaviour [12].

The International Polar Year project [13] used a Conductivity-Temperature-Depth Satellite Relay Data Logger with southern elephant seals to quantify how animals respond to differences in the environment because the seals' behaviour and population trends signal prevailing conditions for multiple marine habitats. The research collated estimates of population size to determine the number of southern elephant seals in the Southern Ocean, comparing these to published numbers to determine overall change.

Twenty-six baboons were each equipped with a smart collar that embeded a tri-axial accelerometer and GPS to identify running, walking, sitting, standing, and feeding activities. The system fuses sensors data to perform intelligent behaviour identification, allowing for automatic activity profiling by using the ethologists' agreed activity identification system and avoiding prior subjectivity in categorising activities [14].

3.2. Non-wearable technologies

We reviewed non-wearable technologies for monitoring welfare and identified five main categories: (1) PAM (passive acoustic monitoring), (2) camera traps, (3) remote video camera systems including CCTV, (4) additional technologies, and (5) drones.

PAM (passive acoustic monitoring)

Passive acoustic monitoring (PAM) is a non-invasive method for surveying wild animals using remote acoustic technologies such as microphone arrays, hydrophones, or other autonomous recording devices [15]. While PAM is used effectively in wildlife and agricultural animal welfare, it has limited use in zoos, impacted by privacy issues for keepers and zoo visitors (conversations among the zoo staff, between the public etc.), so we have not expanded on this technology here.

Camera traps

Camera traps are remote devices equipped with sensors (e.g., motion, infrared) that record images or videos automatically. They are an important wildlife research tool that offer a practical approach to answer questions about wildlife beyond density or estimation of animal populations [16]. For example, camera traps allow researchers to determine the presence of rare species and sometimes reveal how to better support their recovery [17]. When used in combination with telemetry, they are useful to examine scavenging behaviour [18]. Camera Base software is a tool that helps biologists manage data from multiple camera trap surveys and provides tools for data analysis including capture-recapture, occupancy, activity patterns and diversity [18]–[20].

[20] compared the efficiency of arboreal camera trapping with line transects for inventorying medium and large-sized arboreal mammals and assessed the viability of using camera traps in trees to model habitat occupancy. Cameras recorded 10-sec video clips for ease of identifying species with 200-300 videos processed per hour. Videos can be reviewed at double speed and analysed in statistical software.

Collaborative wildlife monitoring and tracking large geographical and time scales with volunteer citizen scientists using camera-traps (motion sensitive cameras) has expanded conservation research [21], [22]. Priorities identified for future improvement include automated camera-trap image analysis for animal detection, tracking, species recognition, advanced machine learning and image analysis methods to improve performance and successful deployment. 2.6 million images of several North American mammals were processed using eMammal, a biological informatics cyber-infrastructure, which brings together citizen scientists and wildlife professionals to collect, analyse, and manage massive camera-trap data. The system comprises: (1) software for viewing, tagging, and uploading photographs, (2) expert review to ensure data quality, (3) an archive for approved data, and (4) a website for managing the study, including the participants, and accessing and analysing the data. Macrosystem scale monitoring of wildlife by volunteer-run camera traps could produce the data needed to address questions concerning broadly distributed mammals and raise public awareness of conservation science.

Using 83 camera traps (Bushnell Trophy Cam™), researchers examined the accuracy of camera trap data to provide assessments of chimpanzees (Pan troglodytes) party size, seasonal variation in party size, community demographic changes (births, deaths, emigrations, immigrations), and community composition (age/sex structure) and habituation to camera traps [23] .

A photographic capture – recapture survey used remotely triggered modified and installed Pentax ‘point and shoot’ cameras in a waterproof plastic box with a receiver and separate wireless passive infrared trigger. Later modifications enabled infrared images. Remote RFID (Radio-frequency identification) scanners have been deployed in a range of situations for passive monitoring and work well in the wild to record the diversity of co-occurring species [24].

Bushnell camera traps with infrared sensor and low glow LED flashs, equipped with SD cards and lithium batteries were left in place to take bursts of three pictures [25]. Camera trapping combined with citizen science was efficient for long-term non-invasive monitoring at low cost.

A remote camera trapping method took images and video, providing identification of individual free-roaming wild horses across a range of habitats and capturing multiple animal-based welfare indicators. This was useful where horses could not be sighted regularly, for a long enough duration or approached closely enough to enable direct assessment of welfare. Precise, strategic camera placement and settings enhanced quality of the data and minimised battery usage and SD card storage [26].

Comparative Review

Comparative testing of the five most frequently used camera traps [27] (Bushnell Trophy Cam Aggressor, Keep Guard 680V, Ltl Acorn Ltl-5310, Scoutguard SG550BV, and Reconyx HyperFire) identified key factors influencing the probability of successful usable photographs. Performance differences from varied settings demonstrated caution is needed for direct comparisons between results of different experiments, or when designing new ones [27]. [28] compares three commonly used camera traps (Reconyx PC850, Scoutguard KG680v, Bushnell Trophy) used for monitoring behaviour of fauna, general survey of fauna and detection of medium to large terrestrial animals to improve fauna conservation.

Testing in the Zoo with Trail Cameras
Trail cameras were tested in three zoos; Auckland Zoo, Hamilton Zoo, and Currumbin Wildlife Sanctuary to examine how red panda would respond to these cameras within the context of gauging their usefulness for wild settings. [29] used two main types of cameras: a Kinopta Blackeye BE2-W ('Blackeye') and two different models of trail cameras: a Bushnell Trophy Cam Aggressor and Browning Dark Ops sub micro-series. Direct personal observations were also taken, noting typical significant factors, such as weather and temperature. Statistical analysis demonstrated a significant difference in types of behaviours recorded with the two observational methods, exposing that method does affect the type of data collected. Trail cameras affected behaviour at all zoos by changing the way red panda spent their time, with captive red panda more active when in trail camera presence. Temperature also had a significant impact with red panda sleeping and resting longer at higher temperatures. As trail cameras changed the way red panda spent their time (in a captive setting), care should be taken for using trail cameras in the wild to compensate for inflated activity estimates.

3.3 Merging wearable and non-wearable

Advances from camera trap array data (Reconyx infrared cameras) paired with data collected from GPS (wearable) tracking collars (containing a triaxial accelerometer, and ultra-high-frequency transmitter for telemetry and data download) was used to detect whether, at the population level, the spatial and temporal patterns of detections reflected the proximity of space use to sampling sites, or variability in the magnitude of animal movement across the area [30]. Not accounting for multi-species movement may bias inferences of ecologic processes and result in mis-specified recommendations.

Nonwearable Wildlife Advanced Monitoring Camera (WAMCam) and wearable (smart collar) monitoring technologies were combined [31]. WAMCam is a smart camera unit, connected by satellite communications and backed by a system control panel to manage a collection of deployed devices [32]. This system combines several WAMCam smart devices, communicating over LoRaWAN with a SATCOM gateway device. The rugged, battery-powered cameras are designed with AI onboard, capable of identifying difference species of interest. WAMCam devices monitor live animal traps and send notifications to the end user when the trap is triggered via SMS and/or email in real time. To minimise cost, the WAMCam system uses Iridium SBD messaging to notify the user of the animal trap status and contents. Small, text-based messaging works for sites with satellite visibility issues. SBD messages are received at the ground station and forwarded to the Cerebella middleware, where they are processed and passed to the end user as notifications. Frequency of status reports can also be configured remotely. Notifications can include the detected species in the trap or indicate when the trap is empty and was accidentally triggered, e.g., by a falling branch. LoRaWAN allows the user to position the animal trap where required, unconstrained by satellite visibility constraints. The system is configured via the web-based Cerebella control panel where devices are managed, with status updates. Use demonstrated the multi-scale modelling identified primary habitat requirements, limiting factors and the spatial scales at which organisms are strongly associated with key habitat factors. The projected model provides crucial information for conservation management, including the identification of suitable core habitats and medium-quality habitats, critical to meta-population viability through provisioning of essential connectivity corridors for dispersal and mating among core populations.

3.4. Remote video camera systems

Remote video camera systems are also useful tools for monitoring animals. Video cameras can facilitate around-the-clock monitoring of animals, providing visual access to their natural habitat where direct observation would be difficult. Observing animals via video surveillance can provide an in-depth, intimate look into their behaviour and may reveal unique behaviours particular to day or night [33].

Remote video camera systems, or closed-circuit television (CCTV) cameras, come in many models, including analogue CCTV, digital CCTV, wireless/wired systems, HD-TVI CCTV, IP cameras (advanced CCTV), portable CCTV, or trial cameras. The CCTV camera lens focuses light onto a sensor. Electronics convert this signal to analogue video. Some cameras include audio. Wildlife CCTV cameras often need an infrared LED light source to cover nocturnal animals. During the day, sunlight is reflected from the animal for the camera to produce a colour image. In low light, the camera uses its own infrared light source to generate a black and white image.

CCTV cameras can be waterproof and weather resistant. High-end cameras use an IP rating where IP stands for International Protection marking. The most suitable rating range is IP65 to IP68; where the first digit 6, denotes dust tight, the second depicts water tolerance. For IP65, the camera withstands jets of water. For IP68, the camera can be submerged. IP65 to IP68 are waterproof in heavy rain.

Analogue HD system (HD-TVI CCTV) deliver high-quality video. With higher-quality images, HD-TVI use longer lengths of cable without signal loss and delivers excellent colour saturation. The cost depends on size and signal quality. Image quality is described in term of TV lines (TVL). Standard analogue cameras with 600 TVL are not expensive, where 1,000 TVL are high-resolution and more expensive.

Live feed is usually viewed through a monitor in a control room, particularly when used for security and safety measures. Better recorders have motion detection. Trail cameras depend on detecting changes in heat, rather than motion. Capture devices often include software and screens for direct video viewing. More than one camera stream requires a connected capture card or PC software to set up motion detection parameters.

All CCTV cameras need a power source. Most use mains power (wired), but some are wireless. A wired system requires a wire for power attached to the video and one connected to the camera. In a wireless system, the camera signal is transmitted through the air, but power is still needed by the camera, either by cable (removing the advantage of wireless systems), or by battery (which needs regular recharging). Solar panels can charge the battery and be mounted close by.

Once videos have been reviewed, selected videos can be exported in short clips and edited in a video-editing package. Data analysis can be done manually or via machine learning. Remote video camera systems monitor day and night cycles of animal life with many applications for CCTV [34]. [34] makes recommendations on monitoring wildlife with low-cost solutions to make CCTV more accessible to wildlife practitioners and naturalists. [35] provides recommendations for animal facilities on installing systems. They outline the benefits of camera systems for sanctuaries to facilitate animal care and observational research. [36] identified costs, maintenance logistics, and location as issues and recommended use for easily identifiable behaviours. [37] used CCTV for sleep monitoring combined with cortisol measuring for stress testing to assess animal welfare states.

Examples of Use in Zoos

We summarise here examples from the literature review of successful application of CCTV in zoos and the combined use of multiple behavioural observation technologies, including camera traps, and programs like ZooMonitor [1] to gather information on activity budgets, habitat use, and social interactions. These in turn inform management decisions to improve the welfare of animals in their care.

Chester Zoo, UK used video surveillance system Axis IP cameras in combination with Milestone's XProtect video management software, enabling personnel to monitor live views and easily search and quickly retrieve footage from recordings [38].

Birmingham Zoo, Alabama, USA used high-resolution cameras in MOBOTIX surveillance system to enhance zoo security while collecting critical information on animal behaviour. [39] recorded elephants' behaviour and used a portable MOBOTIX camera to monitor a pregnant female orangutan that recently gave birth. The event and the baby orangutan's first days were available viewing for zoo officials through remote access, providing detailed scientific data than was previously possible. MOBOTIX is a decentralized video system and includes professional video management software, to allow unlimited users, layout editor for floor plans, interface and camera view and reduce the numbers of cameras needed by incorporating a high-speed computer into every camera. This reduces network bandwidth as video footage is processed within the cameras. One MOBOTIX camera with 3.1 megapixels records more detail than traditional CCTV cameras with larger image areas of up to 360-degrees [39].

A combination of a Genetec closed-circuit infrared camera system (CCTV) (Genetec Security Center), five camera traps (Bushnell Trail Camera Trophy Cam HD), and Zoo Monitor (mobile application software) were used for behavioural observations for one male and six female Asian elephants in The Smithsonian's National Zoological Park (NZP), USA [40]. They compared video and image capture methods to examine activity budgets, habitat use, and social interactions. They found camera traps were a reliable technology for comprehensive, 24/7 surveillance of animals in zoos that cannot install CCTV. Either method can be used to determine accurate activity budgets or habitat use. 30-minute focal observations via ZooMonitor better described changes in social interactions over time.

CCTV can also be used to livestream activity using live streaming capable IP cameras to YouTube or other platforms, such as Panda Cams (YouTube & Live PandaCam) Zoo Atlanta, USA [41]. The Dublin Zoo, Ireland has live webcams on their wolves, penguins, elephants, and animals from the African Savanna area with the aim of motivating conservation awareness through bringing animals and humans together [16]. Baseline data on the Dublin Zoo herd of Asian elephants added to existing knowledge on locomotory behaviour of elephants in urban zoo environments and provides a basis for future welfare recommendations [42]. These elephants displayed behaviours and travel distances comparable to those in the wild [43]. Data was collected without disturbing elephants' usual routines. The work promotes monitoring technology use in further zoo studies, alleviates the need to attach sensors to animals and enables footage to be played in real time or viewed later.

Delhi Zoo installed CCTV cameras (n=230) on the premises and in animal enclosures, for 24/7 monitoring of animal and human behaviour [44]. The zoo plans to introduce virtual reality technology, to allow visitors to "get closer" to the animals, and a GPS-based mobile application to make zoo visits more engaging and informative. The technologies can provide dependable behavioural information 24/7 while minimising time and resources used in long-term monitoring. Long-term behaviour data can be integrated into zoo management strategies to respond to the changing needs of animals to social, environmental, or physical changes.

The Association of Zoos & Aquariums (AZA) Animal Welfare Committee recommends that zoo professionals develop tools for measuring zoo animal welfare on an individual animal-based level. Multiple zoos and aquariums have developed their own assessment tools and programs. These include EthoTrak® (developed by the Chicago Zoological Society), EthoSearch (developed by Lincoln Park Zoo and partners), ZooMonitor (developed by Lincoln Park Zoo and partners), WelfareTrak® (developed by the Chicago Zoological Society and partners), and the geriatric animal quality of life assessment process developed by San Francisco Zoo's Wellness and Conservation Center. These tools are provided for the zoological community to engage in on-going behavioural monitoring and facilitate a continual assessment of animal welfare. Some are offered free to Accredited Organizations (Zoo, Aquarium, Sanctuary or Museum). For example, ZooMonitor is a popular free application used in many zoos including the Smithsonian's National Zoological Park, North America, the sanctuary Chimp Haven, Shreveport, LA, etc. Companies selling technology may supply their systems with inbuilt software, such as Gview, supplied as part of the CCTV system.

Examples of Use on Farms

CCTV is also used for monitoring livestock in the farming industry. With increasing farm size and diversity of tasks, farmers can benefit from automatic animal behavioural surveillance [45]. A system based on Internet of Things and machine learning cameras (cv2.VideoCapture) with environmental sensors for ambient light, NH_3, H_2S, CO_2, temperature and humidity was used for evaluating the health and welfare of goats in precision goat farming to assess their daily behaviour and provide real-time monitoring of their welfare [46]. The architecture of the on-farm monitoring system had several components, including sensing, data transmission, application layers and Wi-Fi-enabled communication and data transmission between the hardware node and remote server. The Faster R-CNN algorithm detected and identified individual goats. Food or water lines were drawn to identify eating and drinking behaviour, so goat behaviour could be classified as drinking or eating once the goat's head was beyond the food or water lines. Economic gains and breeding efficiency were improved with reduced manual labour costs, timely offering of adaptive living conditions, and growth care for goats. As a multifaceted and multilevel monitoring system of goat welfare, this system may provide a useful reference for future precision livestock farming and surveillance.

Surveillance of farm animals and automatic detection of deviant behaviours is evolving in livestock science and farming [45]. [45], [47] use two computer vision algorithms to analyse and record the movement activity of single-housed sows. The system transforms the signal, so sows are reliably detected and monitored, with detection levels customised so unexpected behaviour raises alarms.

3.5. Additional technologies and applications

Many other technologies are used for monitoring animals' behaviour, including, but not only in zoos. [48] used track plates to measure white-footed mouse (Peromyscus leucopus) activity around individual trees over summer to compare track activity to predation rates on gypsy moth pupae (Lymantria dispar) deployed on the same trees. The behavioural response of mice to track plates was evaluated by comparing rates the oat grains placed on and near track plates were consumed. The acetate sheets with a graphite, alcohol, and oil coating had relative superior water-resistance and utility. [48] concluded track plates offer an economical and reliable quantification of local risk of attack by terrestrial mammals without altering spatial risk distribution.

Disney personnel conducted research combining individual animal welfare monitoring with measurement of environmental conditions, (comparing sound pressure levels) to inform science-based animal management decisions [49]. [49] tested foam, plastic, and plywood barriers for efficacy. Sound reduction for all three was greater for higher frequencies vs. lower frequencies. Animal care and science personnel developed a model that tracked animal keepers' daily assessments of an animal's physical health, behaviour, and responses to husbandry activity; these data were matched to different external stimuli and environmental conditions, including sound levels. This approach used elements and tools from various existing welfare assessment programs and emphasised customisation to individual animals to include daily tracking of multiple welfare measures. The objective was to better understand how specific events in their animals' environment influence their welfare and use that information to inform management decisions.

Social Interactions

A collaborative study from Zoos Victoria examined social interactions with technology use between humans and animals [50]. Researchers examined five interactive systems with two used by visitors (Digital Signs and the Zoopermarket), two used by zoo personnel with visitors (Educator Screens and Volunteer iPads), and one used by zoo personnel with animals (Apps for Apes). Use data was gathered from interviews, digital content and observations investigating tensions between technology and the experience of viewing animals and technology and the 'natural' environment of the zoo.

Researchers recommended mitigation via design choices and incorporation of technology into the naturalistic landscape of the zoo [50].

Environmental Temperature

The remote environmental monitoring system Sensaphone WSG30 (wireless monitoring), alarm and event logging system with temperature and power sensors was installed in Elmwood Park Zoo, Norristown, USA [51]. The system watches over areas that house reptiles and monkeys. Temperature is key in this building, because reptiles and amphibians are housed on the upper level and mammals on the ground floor. Each require unique settings. If the system detects a problem, alerts are instantaneous. Additional entry and motion sensors can operate as a whole building security system.

Cardiopulmonary Activity

[52] used digital cameras for basic health checks to reduce anaesthetic use for zoo animals. Monitoring included nine species of zoo animals: giant panda (Ailuropoda melanoleuca), African lions (Panthera leo), Sumatran tiger (Panthera tigris sumatrae), koala (Phascolarctos cinereus), red kangaroo (Macropus rufus), alpaca (Vicugna pacos), little blue penguin (Eudyptula minor), Sumatran orangutan (Pongo abelii) and hamadryas baboon (Papio hamadryas) [53]. The non-contact, non-invasive and cost-effective monitoring system uses digital camera imagery to extract cardiopulmonary signal (PR and BR) of unrestrained animals at different distances detecting motion on the animal body surface caused by cardiopulmonary activity. This novel method provides non-contact physical monitoring and remotely sensed health assessment of animals, demonstrating promise for applications in veterinary practice, conservation, game management, animal welfare and zoological and behavioural studies.

Thermal (infrared)

[54] worked with thermal (infrared) imaging in a sanctuary setting where unrestrained chimpanzees were able to move freely around their enclosures. This was coupled with an evaluation of pairing information with long-term behavioural data for a multifactor welfare monitoring system. Use of thermal imaging in large and complex environments is useful where enclosure elements may otherwise occlude (e.g., trees, low-light conditions) or for e.g., non-invasive documentation and tracking of wound and infection healing from a distance.

Used for observation of wildlife in their natural habitat and overview of thermal physics and the thermal imager, [55] included a manual on sound survey design, theory and performance characteristics of thermal imaging cameras with cooled quantum detectors and uncooled micro bolometric imagers as introduced in past decades [55]. [56] describes how thermal images (or thermographic cameras) work and presents some examples of using this technology in a variety of contexts beyond wildlife monitoring, including research on migrations [57], behaviour (e.g., flight patterns; [58]), welfare and disease diagnosis [59], to avoid killing of animals (e.g., farmland bird nests, fawns) during mowing [60], to detect wind farm collisions of birds [61].

The contrast between the heat emitted by animals and their immediate surroundings can help detect them efficiently and unobtrusively, particularly at night, with cryptic background or when hidden by vegetation [62]. Complexities such as ambient temperature, insulation by fur, surface temperature vs. core body temperature, distance to target, field of view of the lens meant pilot studies/case studies were required. For data collection, thermal imaging is passive under day and nighttime conditions. It minimizes disturbances to wildlife and detects animals which are colder, warmer, or the same as their background temperature because it does not compare temperatures but detects heat emissions of the animal against its background.

Reviews of multiple technologies
[63] reviewed four indirect noninvasive methods for primate conservation —camera traps, acoustic monitoring, drones, and portable field labs—and improvements in machine learning that offer rapid, reliable means of combing through the large datasets these methods generate.

Portable field labs analyse primate faeces for endocrinological, diet, and genetic studies, revealing parasites, diagnosis diseases, etc. Genomics is progressively valuable as a tool in wildlife conservation for species identification and understanding dynamics of endangered populations [64]. It also assists in identifying inbreeding depression, population structure, and impacts of population fragmentation [65]. Molecular epidemiology from genomic data is an increasingly common tool in primate health monitoring [66]. Miniature tools for molecular processing of field samples is now pervasive with portable and compact USB-powered sequencers [67] enabling obtaining data on a wide variety of primates, and analysis of this information on site. There are limitations with infrastructure requirements, cost per sample, necessary equipment, lower throughput and higher error rates [68]. Rapid developments in flow cell chemistry and bioinformatics pipelines can address some of these [69]–[71].

Drones
Drones (also known as unmanned aerial vehicles, UAVs and remotely piloted aircraft systems, RPAS) are remotely operated aircrafts with autonomous flight capabilities. Drone surveys allow rapid and frequent monitoring in remote and poorly-understood areas, with data immediately accessible and rich information on habitat and conservation related conditions [72]. [73] describes a female chimpanzee making two sweeps at an overhead drone with a branch that she held in one hand. The second sweep successfully downed the drone, demonstrating forward planning with tool-use and in this instance, the perceived invasiveness of the drone. [74] and [75] discuss the use of drones for wildlife conservation, including the three common types of conservation drones, outlining the pros and cons of each version. There is much potential for drone use in larger scale environments and for conservation purposes, to detect and monitor arboreal mammal populations and to assess species occupancy and distribution.

3.7. Data analyzing applications (software)

One of the most critical issues in using technologies in addition to data collection is data analysis. Different applications are being developed to combine images and/or video with analytics for smart event detection and automatic control of the technology--reducing or eradicating the need for user interaction or participation. Some species-specific welfare monitoring programs are being designed based on multi-institutional studies that tested many parameters on a single species or taxa. Artificial intelligence is increasingly used to improve wildlife identification, monitoring and analysis of large amounts of conservation data, coming from multiple sources such as camera trap, satellite and drone images or audio and video recordings [76]. Digital tools that increase efficiency in data collection and visualization are becoming increasingly available. [49] points to ideas surrounding welfare that is unique to individual animals and contexts.

4 Questionnaires

To understand what monitoring technologies zoos concerned with animal welfare were already using – and what their 'wish list' for future improvements would be—we sent out five straight forward plain English questions.

1. What technologies do you use for animal monitoring?
2. For what purposes do you undertake monitoring?
3. With which animals are these technologies used?
4. What brands are your technology solutions?
5. In a perfect world, what else would you like these technologies to be able to do?

Using the samples from keyword searches via google and google scholar (e.g., zoo monitoring behaviour remote) using PICO process, we had found a variety of publications and resources that included this list of zoos (see Table 1)—identified as taking a progressive approach to animal welfare [2] . The identified Zoos were:

Table 1. Zoos identified in the literature [2]as progressive in relation to animal welfare and use of technology

- Birmingham Zoo
  B Bryan Preserve
- Caldwell Zoo – Wilder Institute/Calgary Zoo
- Zoológico de Cali
- Cameron Park Zoo
- Chicago Zoological Society (Association of Zoos and Aquariums
- Columbus Zoo & Aquarium
- Hai Park Kiryat Motzkin
- Kaliningrad Zoo
- Kiev Zoo
- Los Angeles Zoo
- Moscow Zoo
- Nikolaev Zoo
- Indianapolis Zoo Simon Skjodt International Orangutan Center
- Zoos Victoria
- Auckland Zoo
- Lincoln Park Zoo
- North Carolina Zoo
- Point Defiance Zoo & Aquarium
- Saint Louis Zoo
- Tharonga Sydney (on the list)
- WAZA (World Association of Zoos & Aquariums)
- Woodland Park Zoo
- Wuppertal Zoo

The approach towards all zoos was via email or where no email contact was available, via their online form queries system. We used the same request text for all enquiries.

Dear [ZOO NAME],

We are researchers at Auckland University of Technology. We are doing a study that involves identifying the best animal welfare monitoring solutions used by the most progressive zoos and sanctuaries. We are looking at technology solutions that help identify and address animal behaviour issues and take the workload off zookeepers.

Could you please pass on this short questionnaire to the right person/people in your organisation? The findings from this survey will be presented in a report, a copy of which can be sent to your organisation.

1. What technologies do you use for animal monitoring?
2. For what purposes do you undertake monitoring?
3. With which animals are these technologies used?
4. What brands are your technology solutions?
5. In a perfect world, what else would you like these technologies to be able to do?

If convenient, can you email me the answers to these questions, or I can also zoom/phone in to discuss depending on what suits you best.

Ann Morrison (contact details etc).

4.1. Responses

Four zoos graciously participated, and we present their responses to the questions here:

What technologies do you use for animal monitoring?

#1 Our main method of monitoring animals is video cameras that are trained on the enclosures 24/7.

#2 For our welfare assessments, we enter the data into ZIMS/Species 360. Keeper staff helped decide what aspects we would like to monitor and then a form was made for them to fill out. Once it is filled out, it is sent to the Animal Care Supervisor of Mammals and our veterinarian for review, then entered ZIMS/Species 360. The hard copies are kept in a file for each individual or in their information folder.

#3 ZIMS. We currently aren't using the Care and Welfare module yet but are planning to slowly implement in the next few months. Internet to look up info or help in creating ethograms. Video/cameras. Thermometers/Hygrometers? For monitoring animal environments. Metasys?

#4 The primary technology that we use for animal monitoring is the ZooMonitor app (www.zoomonitor.org). This is an app that was originally developed by Lincoln Park Zoo in partnership with Tracks Data Solutions, largely funded by the Institute for Museum and Library Services. Trained observers (volunteers, interns, research staff, keepers) watch the animals and record animal behavior and space use on tablet devices (iPads), and the ZooMonitor software provides some basic summary data and intuitive heat maps to visualize how animals are using their habitats. We are in the process of expanding the app to facilitate multi-institutional animal monitoring.

In addition, we use Monnit sensors to remotely detect activity and habitat or feature use (www.monnit.com), motion-triggered or time-triggered trail cameras (e.g., Bushnell.com, www.Wyze.com), and small "spy" cameras (brand = Blindspot). We also have several habitats equipped with 24-hour camera surveillance. We will sometimes extract systematically collected behavior information from our primary record-keeping software, Tracks. (www.trackssoftware.com).

For what purposes do you undertake monitoring?

#1 This enables us to monitor health, behaviour, group interaction, aggression, interaction with devices etc. If and when we detect any concerning behaviour, the caretaker is then instructed to monitor closely in person.

#2 All our animal data is entered into ZIMS/Species 360, so it made the most sense to use that software for our assessments as well. We do not enter the assessments right into ZIMS, in case more information is needed from the supervisor or vet.

#3 Gaining info about animal interactions, conspecifics, and mix species. Parturition. Shifting and moving animals around habitats. Medical or dietary observations

#4 We have an ongoing monitoring program for about 30 species at the zoo (primarily fuelled by our trained volunteers). Some species were originally selected due to questions about their behavior, space use or welfare, but not all. Some were chosen to provide variability of observers, to diversify the taxonomy of our monitored species, or for logistical reasons. Additionally, we initiate monitoring in response to questions raised by animal managers, and in response to research questions pursued by our scientific staff. Often times the projects that are sparked by a question will transition into long-term monitoring, since the initial project foundation has been established.

With which animals are these technologies used?

#1 In principle all the enclosures are under constant passive video monitoring, but if and when there is a particular concern we then switch to active monitoring

#2 In the mammal department, we do assessments on all the individuals. Depending on health and age, we will do them more often. Some individuals are twice a year, while others are four times a year.

#3 All animals but less so with our program animal reptiles/invertebrates

#4 ZooMonitor app has been used as part of an ongoing, long-term monitoring program for the African lion, African penguin, Allen's swamp monkey, American avocet, Asian small-clawed otter, Bactrian camel, Black bear, Black rhino, Black-and-white colobus, Black-necked stilt, Brush-tailed betting, Chimpanzees, Cinereous vulture, Crowned lemur, De Brazza's monkey, Eastern screech owl, Egyptian fruit bats, Giraffe, Golden-headed lion tamarin, Gorillas, Grey seal, Guam rail, Guam kingfisher, Harbor seal, Japanese macaques, Jamaican Iguana, Klipspringer, Ornate box turtle, Polar bear, Pygmy hippo, Red river hog, Snowy owl, Takin, Titi monkey, Three-toed box turtle, White-faced saki monkey and others.

Trail cameras, small spy cameras, or built-in camera systems have been used to monitor: African lions, American toads, Domestic chickens, Dwarf crocodiles, Pygmy hippos, Polar bears, Prevost squirrels, White-blotched river stingray and others. Brush-tailed bettongs and the Armadillo species have been monitored using remote sensors.

What brands are your technology solutions?

#1 Provision

#2 We use ZIMS/Species 360.

#3 Camera software genetic security. Trail cameras all different types and brands. ZIMS.

#4 ZooMonitor app (www.zoomonitor.org), Monnit sensors to remotely detect activity and habitat or feature use (www.monnit.com), motion-triggered or time-triggered trail cameras (e.g., Bushnell.com, www.Wyze.com), and small "spy" cameras (brand = Blindspot). Extract systematically collected behavior information from our primary record-keeping software, Tracks. (www.trackssoftware.com).

In a perfect world, what else would you like these technologies to be able to do?

#1 Measure cortisol

#2 ZIMS/Species 360 does everything that we currently need

In response to further queries on remote in and alerts:

#2 You can access it from home, but I have never tried to set up any alerts. We also have never used it for behaviour analysis. We have used ZooMonitor, but we don't use ZIMS/Species 360 in that form. I am sure it is possible, but we don't use it that way here.

#3 Audio. A perfect monitoring camera would be portable, easy to attach places, weatherproof, have night vision, more recording capabilities, remotely controlled/moveable and viewable, and audio.

#4 We are expanding the ZooMonitor functionality to support multi-institutional data collection which we think is a step in the right direction! In a perfect world, behavioral monitoring apps like ZooMonitor would have built-in analytics that indicate real-time when welfare has likely improved or declined in quality. In a perfect world, there would be non-invasive, accurate, automated recording of behavioral and physiological changes in animals. The remote sensors are typically made for larger animals, people, so more sensitivity for smaller-bodied animals, burrowing animals, flying animals, would be great. Ability to train motion-triggered cameras to the type of motion of interest (e.g., a moving wolf but not a moving stick) and to follow that motion, view the full scene, would also be ideal, combined with automated coding of the recorded information.

4.2. Summary of Responses to Questionnaires

While we did not expect ALL zoos (see Table 1) would participate, we were initially disheartened with so few responses. While understanding the limitations of such small numbers, it was useful to get current information on the monitoring technologies in use at these responding zoos and compare not only the differences between the systems in use, but also what they are used for and their priority focus. Of the first three zoos, one used the system 'Provision' with video cameras trained on the all the enclosures 24/7 for passive video monitoring. If any concerning behaviour was detected, the system was switched to active monitoring, coupled with manual observation from the caretaker. The zoo uses the technology to monitor health, behaviour, group interaction, aggression, interaction with devices etc. For future improvements, the zoo would like to add cortisol measuring to their data gathering to get a better reading of health and stress levels of their animals.

By contrast, Zoos #2 and #3 used ZIMS/Species 360 on the mammal population with the monitoring also used for assessments on all individuals. How often these assessments occurred depending on the health and the age of the individuals with the more fragile being assessed more often (e.g., four times per year versus twice a year). For each individual animal, there was a hard copy information folder where any changes were recorded. The data from the assessments was not entered directly into ZIMS, in the case that more information or assessment would be needed from the supervisor or vet. ZIMS/Species 360 systems catered for all #2 Zoo's current needs but were not using the system for behaviour analysis. #3's priority is to gain information about animal interactions, conspecifics, and mix species.

The fourth zoo is a major instigator in a wider problem-based solution process to fit multiple scenarios. Their responses are comprehensive and detail their historical and ongoing developmental solution-based approach. Their continual expansion of e.g., ZooMonitor functionality is beneficial to many zoos who due to their inclusive approach, also work with this system. As a key-player in developing technology solutions in this field it is useful to note their future trajectory with "non-invasive, accurate, automated recording of behavioral and physiological changes in animals" and "automated coding of the recorded information." Something many zoos, farms and animal wildlife sanctuaries are also looking to implement. In addition, multi-institutional sharing of data, also a conservation imperative, would accelerate knowledge transfer and impact significantly on improvements to animal welfare.

5 Discussion

We have identified developments and implementations in the reviewed literature section 3, versus deployed and future aspirations demonstrated in the zoo questionnaire responses. Here, we combine advances and ambitions from these two sources and discuss limitations, issues and impact, recommendations, and next steps forward. Overall, we note a call for 'non-invasive, accurate, automated recording of behavioral and physiological changes in animals' (#4 zoo).

5.1. Limitations

Since writing up the initial report and this article, we are aware other relevant articles will have been published that we could not include. 'Relatively' new to the field, we took guidance from Auckland University of Technology librarians and conservation researchers on refining our keyword search terms.

The small number of zoos that responded compared to those we approached (see Table 1) is a limitation of the study. Regardless, the responses reveal a diverse set of priorities, focus, and implemented solutions and contribute to the larger discussion.

Not all monitoring technologies are suitable for use in a zoo environment. Drones have a limited capacity with legal and institutional restrictions regarding aviation rules and health and safety. Noise from drones has been identified as a serious disturbance risk for some species in the wild with future aerial survey or monitoring work requiring strict protocols to minimize disturbance risks [77]. Recent novel work determined optimal flight altitudes for minimizing drone disturbance for wildlife using species audiograms [78]. While Passive Acoustic Monitoring (PAM) [15], [79] is useful technology for sound recording and automatic sound identification of animals in the wild [56], [80], use is restricted by privacy issues for zoo environments.

5.2. Issues and Impact

Issues that impact zoo environments more generally include:

Wifi Coverage: The efficiency and capacity of Wi-Fi and the servers the systems run on impacts what technology can be supported and what remote use is possible within zoos [7], [12]. Traditionally zoos' focus was on providing 'natural-enough' enriched environments for the animals and this still fits, but technologies did not play such an integral role. More recent technology interventions require mitigation of technology integration into design choices to augment the naturalistic landscape environments [50].

Public Institutions: Many zoos are supported by public monies and operate on public institution networks or cloud-based services. These have standard restrictions on privacy and data security, plus competition for resources is always a factor within the framework of a large institutional model. Upgrading and adding new software and data analysis systems may cause incompatibilities across entire systems, where numerous functions and institutions need to operate securely within the one multi-serving system.

Public Facing: Keepers and zoos are aware of the need to keep up with the evolving focus on animal welfare, successful breeding (especially for endangered species) and education programs, as well as benefits from using enhanced technology systems. Most important is the re-education of the public's perception of the usefulness of technologies to address animal welfare issues, particularly with e.g., visible wearable technologies for this purpose. Often the public has a mixed perception and reception even of the role of zoos, which requires Public Relations information management. This might take the form of radio and online interviews, newspaper clips and social media promotion that focus on animal welfare benefits. Zoo tours and information sessions already make up many zoo's routines and could include information on the benefits of such technologies. Research studies that demonstrate positive welfare impacts from data gathered through wearables and other monitoring technologies would support an informed public's understanding of these devices as having a positive impact on animal welfare. We also see this in section 3.4, Examples of Use in Zoos, where technologies bring animals and humans 'closer together' through webcam streaming, CCTV and video monitoring, camera traps and VR technology [38]–[44]. These technologies feed information to the keepers and also act to connect and bond the public to the animals whose lives they are able to witness. Events such as the birth of an endangered species [39] provide leverage for updating global technology coverage, promotes the conservation role of the modern zoo and attracts visitors.

5.3. Recommendations & Next Steps Forward

Thermal Cover: Infrared coverage contributes non-invasive animal welfare monitoring. Either in the form of lighting to increase evening image capture quality or with thermal infrared cameras capacity for early detection of changes in the animals and their environments [54]–[60]. Multiple sensors uptake environmental measurements non-invasively [46], with temperature alerts [51], and infrared sensors [25]. Including heat emitted by animals in data collection systems [62] ensures animal detection despite occlusion by foliage, sleeping etc. Solar driven heat cameras can detect animals' physiological conditions 24/7.

Combining Systems: Adaptive modular systems would enable various sensor systems to be combined, proving useful as would combining monitoring methods, e.g., mixing sleep observation with cortisol readings (#1 zoo) [37]. Continuing modification and integration of simple modular systems proves promising. For example, camera traps are mobile, and motion activated—so they can be readily repositioned in response to changing activity. However, they cannot be accessed remotely, need an easy-to-use interface, extended recording capabilities night vision, audio (#3 zoo) and sensitivity to smaller-bodied animals (#4 zoo). Adapting camera traps to manage Wi-Fi and adding a quality interface significantly change capacity. Smaller mobile modular solutions can sometimes be the most useful [31], [32]. Where existing systems can be updated, modified, and/or coupled with several systems offers flexibility and expands data collection capabilities [37]. Digital cameras to track cardiopulmonary readings offer basic health checks [52]. Wearable solutions such as a leg band or collar are possible for some animals [6]–[8], [14] and would prove to be a less invasive solution. Zoo environments require ruggedized solutions to operate in restrictive conditions.

Motion Tracking: Individual ID tracking requires high resolution cameras to allow tracking of individuals, including the type of motion practiced and following that motion within the full scene would also be ideal (#4 zoo) [26], [45]–[47]. Complete coverage and adding motion detection to such systems would assist analysis, particularly when coupled with alerts. Alerts would also prove useful with drones when large zoo animals are transferred to sanctuary type settings, as happens with the progressive zoos. Those animals still need monitoring for support, especially while in transition and adjusting to their new circumstance [38], [39],[53]–[55], [59], [63][72], [74], [75], [81].Useful also for monitoring in wildlife sanctuaries or for wildlife per se.

Remote access: Secure robust Wi-Fi coverage throughout zoo environments can expand viable coverage options and solutions [46]. In turn, this would provide remote access to monitoring systems [39] [51], reducing manual labour significantly and ensuring systems could adapt easily to the changing needs of animals synchronously. Looking through a 24-hour cycle of footage (even with sampling or fast forwarding) to find anomalies is inefficient use of keeper time. A significant improvement would be to enable alert notifications in condition changes to be reported and received instantaneously [38], [39], [51]. A system of remotely accessible in-situ transponders would enable keepers to note trends vs. established stress baselines. We see this where precision farming captures only above defined baseline parameters of 'usual' behaviour, customised levels are adaptable and unexpected behaviours raise alarms [45], [47]. Autonomous systems to manage data collection and analysis would also inform longer term welfare management strategies and address welfare needs

Data analysis: Efficient data collection, digital tools and visualisation addressing individual animals unique welfare needs and contexts are becoming increasingly available [49]. Zoos and technology developers have recognised the need for an Artificial Intelligence system or similar to analyse large amounts of data from multiple sources [76]. Combining data capture with automated coding of the recorded information would be ideal (#4 zoo). In addition, a long-term archive [21], [22] would map improvement or deterioration of the different species and sanction resources more effectively for future strategic planning, as would multi-institutional sharing of data collection.

6 Conclusion

We investigate the status of contemporary monitoring technologies for animal welfare in a review of the literature. With a focus on zoo environments, we included agricultural and wild environment solutions, as knowledge and applications from those contexts may be transferrable to zoo environment requirements. Responses from zoos working with multiple species with distinctive needs reveal current and future requirements envisaged for the animals in their care and for streamlining workload for the keeper teams. We discuss those expanded desires and aspirations against findings from the literature to scope future improvement solutions for monitoring welfare in zoo environments. We contribute findings, recommendations, and next steps from these scenarios that can be applied more broadly to other animal welfare contexts.

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