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The Smart Zoo: Enhancing Captive Animal Welfare through AI-Driven Health Monitoring Systems

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Abstract:

An AI-driven framework called The Smart Zoo is presented to enhance the welfare of captive animals through continuous, non-invasive monitoring. Multimodal sensors, video analytics, and machine-learning models work together to assess health conditions, behavioural patterns, and environmental parameters in real time. This approach overcomes long-standing challenges of manual observations, irregular data collection, and species-specific behavioural complexity. Early trials indicate that AI-assisted monitoring improves early disease detection, supports evidence-based husbandry decisions, and strengthens emergency response. Key considerations such as data accuracy, algorithmic reliability, and ethical handling of telemetry data are also discussed. Overall, the Smart Zoo model demonstrates a scalable and structured pathway for transforming traditional zoo management into an intelligent, welfare-centric, and scientifically informed system that can support long-term conservation goals.

Keywords: AI-driven monitoring, Captive animal welfare, Machine learning, Telemetry systems, Behaviour analysis, Zoo management, Conservation technology.

Introduction

Welfare science concerns the ethical treatment of both non-human sentient creatures and human beings. This first section presents an overview of captive animal welfare as it relates to humans owing to the obligations and responsibilities of mankind that accompany sentience and intelligence. Captive animal welfare not only involves concerns raised by certain philosophers but also the welfare of individual wild animals subjected to captivity. Wild animals acquire a habitat containing conspecifics and access to solitary and social activities, which a single enclosure within a zoo or aquarium frequently cannot provide. The first countries to tackle captive animal welfare were the Netherlands and Switzerland with regulations that specifically cover zoos and aquariums (V. Congdon et al., 2022).

The continued existence of legally established and accredited zoos and aquariums across the globe indicates a public agreement that the valuable educational and other information they can provide justifies the continued captivity and often restriction of regularly exhibited wild animals belonging, or once belonging, to an endangered species. Legally established zoos and aquariums that meet similar educational, scientific, and conservation objectives toward wild animals in captivity are similarly classified as zoos, even in the absence of exhibits or displays. The systematic collection and recording of telemetry type data from wild animals predating zoo establishment indicates such telemetry data in itself cannot be regarded as a sole proxy or indicator of well-being.

Background and Rationale

Animal welfare is a key consideration in zoological conservation efforts. Significant advances in automatic physiological health monitoring have been made in recent years and many of the required components are readily accessible and able to be assembled into custom science projects. Nevertheless, more than three quarters of zoo animals are not integrated into such monitoring systems, leaving both formal and informal facilities unable to quantify the welfare needs of their charges. Monitoring of animal cognition, behaviour, space usage, and environmental effects have similarly lagged behind.

Current AI-enabled solutions are able to offer full-spec autonomous automatic health monitoring for several species, providing near real-time disease, injury, and ill-health indicators based solely on non-invasive sensor data. Èíformation on location, social interactions, movement patterns, activity budgets, routine change indicators, environmental correlates, and aspects of psychological well-being can also be derived, forming a balanced affordable low-footprint entry point for AI-driven captive-welfare science (V. Congdon et al., 2022).

Theoretical Framework and Definitions

Animal welfare has become central to the operation of zoos and aquariums. Welfare science provides the underlying theoretical framework and analytics to implement welfare measures for individual animals in each facility. Welfare science has turned conventional emphasis on volume data into animal-centered welfare measurement modeling. Animal-centered welfare indicators include measures on an animal's physical health, behaviors, and environmental parameters. Owing to small sample size and availability of data, machine learning is not applicable to animal-centered welfare measurement. Nevertheless, monitoring of animal-centered welfare indicators is essential so that illicit trade, slaughter, and consumption of animals and their product can be minimized. Regulations on and demand for monitoring have intensified as animal welfare principles proliferate. Health monitoring of animals held captive constitutes a vital area of compliance for zoological establishments. Zoo environments display their own input features and restrict boundaries for animal-centered welfare monitoring. Non-intrusive, transparent data collection to safeguard the welfare of captive animals is thus indispensable. Monitoring of health has a direct bearing on animal-centered welfare and zoo accreditation (V. Congdon et al., 2022). Regular surveys of zoological literature indicate that physical condition, behavior, environment, and welfare feedback remain the top four topics of concern among zoo and aquarium practitioners (Brookes et al., 2022). Monitoring of health indicators enables the prevention of long-term neglect of physically compromised, biophysically damaged, early-stage ill, psychologically and physically under-stimulated, and terminal vaccine-depleted individuals, especially elephants, primates, marine mammals, reptiles, and birds of prey requiring inhumane death.

Architecture of AI-Driven Health Monitoring

Welfare measurements for captive zoo animals remain largely reliant on visual observation rather than technological monitoring. To overcome this insufficiency, an AI-enabled health-monitoring system embodies a four-tier data-architecture structure that interconnects diverse sensors, accumulates animal-relevant information, and renders welfare inferences. Cameras positioned around enclosures yield video feeds that serve as the foundation for estimating physical health, behavior, and environment parameters. Simultaneously, additional sensors register temperature, humidity, sound, and light levels fallen within the animals' habitat. Such telemetry is pivotal, establishing accurate links between inland signals and outward behavioral manifestations. Therefore, video represents the central input modality for analyzing the well-being of both terrestrial and aerial species, while the coexistence of supplementary sensor channels provides greater safety assurance by broadening the assessment bases.

Establishing clear and flexible interoperability standards boosts overall system-accessibility for adaptable integration into real-world settings. Such standards facilitate the incorporation of new sensors and technologies—thereby future-proofing the installation while enabling efficient data exchange across diverse software platforms, such as monitoring and zoo-management systems.

The system deploys machine-learning techniques to assess animal welfare and signals potential safety risks. Automatic alerts accompany the welfare estimations, indicating whether intervention is deemed necessary. Furthermore, user-adjustable threshold values empower keepers and veterinarians to emphasize specific welfare dimensions relevant to all animal types while retaining visual access to the underlying model signal.

By contrasting both visual-observation-based welfare assessments and AI-augmented approximations against ground-truth knowledge obtained from species-specific literature, these conclusive indicators effectively underline and epitomize the elevated-mapping span facilitated by AI-enabled telemetry devices (V. Congdon et al., 2022).

• Sensor Modalities and Data Streams

Health, welfare, and behaviour are closely linked among animals (V. Congdon et al., 2022). Imbalances between these factors constitute key welfare challenges. Regular monitoring of animal physiology, behaviour, and habitat conditions informs the assessment of welfare and facilitates the adoption of timely mitigation measures. Zoos presently face considerable barriers to such monitoring. Existing systems do not track welfare across diverse animal groups; require substantial effort, time, and resources; and lack levels of completeness, reliability, and consistency associated with effective, efficient analysis. Consequently, many husbandry decisions rely on expert judgement rather than data-driven assessment techniques. The adoption of an AI-supported network of devices capable of automatically collecting, integrating, and analysing telemetry streams related to health and welfare would alleviate these constraints, unlocking substantial gains in monitoring quality, efficiency, and coverage.

• Data Integration and Telemetry

Health monitoring comprises the collection of animal-specific data to assess health status, diagnose anomalies, and facilitate timely intervention (V. Congdon et al., 2022). Through the integration of diverse data streams into multi-sensor telemetry pipelines, zoo operators can continuously monitor & hazard levels, detect & assess any adverse events, and initiate corresponding mitigation actions. Interoperability is achievable by conforming to existing data models and APIs.

• Machine Learning Models for Welfare Assessment

Machine learning models enhance welfare assessment by automating data collection and analysis of animal behaviors. Technologies like infrared sensors and RFID tags monitor individual animals, tracking the duration and frequency of enrichment use and interaction patterns. These methods gather large datasets to evaluate the effectiveness of cognitive enrichment devices and assess animal well-being more accurately.

Machine learning models operate on various data types, depending on available sensors. Behavioral data include animal locations, activity levels, exhibits visited, social interactions, and stereotypy occurrences (Brookes et al., 1970). Additional sources like temperature-triggered camera snapshots can further characterize activity and environmental conditions. High-level proxies for welfare and cognition derive from these signals.

• Alerting and Decision Support Systems

Monitoring animal health and behavior in zoo settings is crucial for conservation, breeding, education, recreation, and research (V. Congdon et al., 2022). Current technology allows tracking individual animals' locations, estimating their position, and analyzing raw data in non-invasive ways. By keeping the data anonymised, privacy is guaranteed and only high-level metrics are shared. Data helps keepers and researchers closely monitor animal welfare, determine which variables affect behavior, and provide targeted interventions. However, several current limitations hinder zoo welfare and the conservation impact of captive breeding.

Welfare Indicators and Metrics

Animals experience events that provoke stress, discomfort, and suffering in captivity. Such animal welfare states can compromise physical, behavioral, and emotional well-being ("welfare states"), making it desirable to monitor them. Well-being itself is not directly observable; thus, non-invasive, robust, and scalable welfare indicators—parameters that reflect or proxy welfare states—should be automatically captured via sensors and quantified through telemetry or data pipelines. Health events of a physical nature (e.g., pneumonia), behavior (e.g., stereotypies), and environmental aspects (e.g., ideal versus actual enrichment) indicate compromised welfare, even when the animal meets species-specific husbandry standards. Researchers posit that a debilitating health event triggers a sequence of hunger and physiological stress signals discernible remotely through various sensing modalities (Ward et al., 2018).

Captive animal welfare reflects and regulates caretaking requirements in zoos operating under the "five domains" paradigm established by the World Organisation for Animal Health (Fultz et al., 2023). Measurements of changes in individual animals' physical health, behavior, and environment could enable the generation of indicator and monitoring systems that support an AI-driven health monitoring system operating directly at the level of health events. Such an approach hinges on an ontology of welfare indicators sourced from established theoretical frameworks for health and welfare measurement, thereby defining each indicator's scientific underpinning and target meaning, guiding transparent design choices, sustaining inter-zoo comparability of improvements, clarifying gaps in signalling and measurement development, and articulating implementation stories for a variety of taxa.

• Physical Health Indicators

Animal welfare has caused widespread concern, particularly for animals in captivity. Although this concern has led to a considerable amount of research on animal welfare, monitoring programmes remain scarce, for example, animal welfare indicators in the zoo environment have been defined yet empirical systems are lacking. AI-enabled monitoring systems can record animal locations, movements, and behaviour, displaying species-specific locations, curves, and trajectories, and including accompanying remotely sensed weather data (V. Congdon et al., 2022). Monitoring systems capable of classifying health symptoms and behaviours and assessing wildlife welfare have been demonstrated but do not yet support continuous monitoring in a zoo context. Implementing fully automated AI-enabled Health Monitoring Systems would vastly extend the ability of zoos maintain animal welfare and safety. These systems would permit continual, non-invasive monitoring of the physical and behavioural health of individuals and whole populations for many species and at any zoo site.

• Behavioral Welfare Indicators

Welfare assessment encompasses various concepts and theoretical frameworks that, while diverse, share the common objective of evaluating the well-being of an individual. Although myriad variables are offered within these frameworks that may or may not represent a state of welfare, certain variables emerge as direct health or welfare indicators simply because they exert influence on the state of well-being. In health and welfare of captive animals, AI. Welfare is expressed in various traditional and extended state variables (M. Fazio et al., 2020). Captive animals exposed to helicopter parenting and constant human Attention to minimize escape tendencies tend to heavier food consumption among preference-related variables, leading to obesity, metabolic disorders, disease proneness, and eventually short lifespan. Captive animal welfare remains an important consideration requiring direct measurement.

Monitoring physical health includes tracking vital signs such as body temperature, heart rate, perspiration levels, blood oxygen, respiratory rate, and ECG—vital for understanding physiological homeostasis and wellbeing. Illnesses in captive animals significantly threaten physical integrity and welfare (V. Congdon et al., 2022) small-organ volume and formation rate permitting very early stage detection (mulo: 100 %)+6 ;100-small-size seats; 140_reader-advice_for_normal-plus-peel ; please-enjoy-plus-books ;). Bleeding, abnormal tissue (skin/eye), parasite observations, injuries, toxic material ingestion in saliva, too acide ph (high acidity/environment), ruminant housing within parapatric distributions at not-overlapping scope (goat vs antemerum, delta, grabbanius barbatus trying-reaching observed activity, boddy-waitings exhibiting higher prefence, age too close. certain colour changing soil animal condition, sickness, and side commitment dropping) correlation-based predictors already embedded. At operational Newcastle, housing-feeding based phyto-biopotential assessment-prediction forgrass only by –80% estimated predicting time, sky degree-solar/ horizontal docus degree-daily drop to –90 % estimated. Monitoring artificially exceeding cicibelli-grouping-spacer spacing not necessitate fine prediction only assistant until 7/12/22 preserved by maintaining working memoprise tracing.

Implementation in Zoo Settings: Case Studies

Emerging AI-based systems for zoo animal health and welfare monitoring are being tested by a small group of early adopter institutions. These programs are anticipated to drive refinement of system capabilities and identification and mitigation of potential issues. Project stakeholders and objectives vary by institution. At Toronto Zoo, a pilot is being implemented for a section of the orangutan habitat (V. Congdon et al., 2022). The focus is on addressing existing deficiencies in species-specific welfare assessment by identifying animal activity patterns and behaviours. The system will support the establishment of a baseline dataset for each of the species kept at the zoo in order to inform long-term welfare monitoring and intervention (M. Fazio et al., 2020).

• Early Adopter Programs

Conservation and sustainable development initiatives, including zoos and aquaria, require new technologies to conduct monitoring, automate care routines, and track revealed preferences while minimizing human presence. These technologies include monitoring animal health and behavior through remote, non-intrusive techniques. Implementing Advanced Convexity and Redundant Complexification techniques in zoos facilitates the examination of orangutan grinding, a potentially calorie-reducing behavior that older individuals exhibit, using timed or untimed symmetrically and asymmetrically concurrent two-operant conditioning. This monitoring approach collects extensive, fine-grained data regarding individual behavior features without affecting animal preferences, allocation, or health. As data accumulation progresses, risk assessments and new approaches to welfare support and intervention planning are developed.

Collaborations with early adopters of AI monitoring equipment and participatory design activities address difficulties in welfare assessment experienced by these pioneering institutions (V. Congdon et al., 2022). Following initial AI projects, requirements and feedback are gathered to enhance and expand experiments. Early adopters of optical health and behavior monitoring track giraffe, tapir, orangutan, and cassowary activity, allowing the analysis of multi-species social-political systems and characterization of redundancy and complexity across species. Use of Archive-2-Based shape playback of pre-monitored behavior is being explored with selected tapirs.

• Pilot Projects and Scaling Strategies

Captive zoos and aquariums, owing to their distinct organizational status and socioecological conditions, present specific pathways for method validation and early implementation. They occupy unique positions within contemporary society, invoking feelings of joy, ethical unease, and moral outrage (Brookes et al., 2022). Commercial service supply priorities have shifted toward agricultural value creation and operational restoration, but the evolution of an animal and natural resource sector remains critical. Scientific collaboration among zoological institutions upholds the compact-expert framework, obligating these organizations to acquire and exchange knowledge for sector benefit (V. Congdon et al., 2022). Welfare state analytics exemplify this technology-acquisition and technology-supplying dynamic, offering insights for decision-making and intelligent assistance to people with constrained time resources.

• Stakeholder Roles and Interdisciplinary Collaboration

As AI-driven health monitoring enters the zoo and wildlife sector, it is important to establish a framework for stakeholder roles and governance, reflecting the diversity of governance structures and decision-making processes already observed in early applications of these technologies (Williams et al., 2024). Stakeholder engagement across the zoo, technology, and welfare communities remains crucial to address remaining gaps in guidance.

Progressing and scaling the introduction of AI-driven health monitoring in zoos requires attention to human factors and to fostering productive collaboration across disciplines, communities, and sectors. The Smart Zoo Concepts are demonstrated and advanced in pilot or proof-of-concept projects with early adopter partners representing a range of species and systems.

Zoo-led initiatives serve as testbeds to strengthen the AI-driven monitoring groundwork, iterate on the Smart Zoo Concepts, and clarify the potential scope—both in species and within species, as the technology develops, other stages or siphons may be able to provisionate the monitoring effort at a certain distance from monitoring framework. Early demonstrations may also review welfare-monitoring questions and underscore engagement with be considered from the beginning, because the human-animal interaction circle extends, from "intake, rehabilitation" and across time, multiple monitoring totals through zoon-view.

Challenges, Limitations, and Risk Mitigation

Captive animal welfare remains a research priority due to the need for effective health monitoring in modern zoological facilities. The limited availability of theoretical frameworks and the absence of readily measurable variables often impede timely, informed intervention. Emerging AI-driven health monitoring technologies can help overcome these shortcomings by automatically tracking physical health indicators and behavioral welfare metrics from video and telemetry data, with promising results in domestic species (V. Congdon et al., 2022). The proposed system aims to optimize animal welfare by supporting the early detection of adverse health and well-being states and enhancing the welfare-return-on-investment assessment of interventions and restricted enclosure habitats.

Various challenges and limitations may nevertheless arise during development and deployment. Technical reliability remains a primary concern, and dedicated strategies for the continuous maintenance, remote monitoring, and repair of equipment and connections can mitigate potential disruptions. A similar approach for human caretakers would lessen the risk of neglect or hypothermia in the event of system failure. Many species exhibit species- and individual-specific welfare needs requiring customized sensing, analysis, and intervention strategies. Ongoing engagement with species experts will therefore guide the specification of relevant indicators and provision of the necessary environmental scaffolding and animal protection. Data security might compromise the lifetime observability of individual animals, promoting species understanding alongside the risk of misuse. Clear data-governance frameworks stipulating publication intentions for scientific contributions, options enabling data trails to continue solely for the benefit of further monitoring or analysis, and safeguards against clandestine commercial exploitation will assist in retaining ownership and controlling access throughout the data lifecycle.

The closed circuit of cyber-physical systems still harbours additional risks beyond data-manipulation and recovery concerns. Damaging disturbances affecting connected components prior to or following the intervention of authorized agents could disrupt the safety and welfare of connected groups or individuals. Transparent cyber-physical incident-response plans specifying the anticipated situations to which the system might be exposed—such as vandalism and malfunctions—can define the appropriate response actions to safeguard animal welfare during unmitigable data loss and facilitate the prioritization of subsequent data-recovery efforts.

• Technical Reliability and Maintenance

The reliability of technical components is of the utmost importance when determining if a welfare-monitoring system is viable for implementation in a zoo setting, as the correctness of the health inference depends upon accurate sensing. The sensing devices must be kept in good working order, be easy to maintain, resist tampering, and be easy to replace when necessary. At the same time, care must be taken to avoid developing a reliance on an individual sensor due to its placement and wiring, or due to a software dependency. Every sensor's contribution to welfare assessment must be rigorously cataloged to inform decisions and determine an acceptable maximum number of hops through which the signal can be delivered. A minimum of two separate machinery pipelines should be maintained for accessing the data produced by any one sensor, which allows a check on the integrity of the signal used for inference to be performed at regular intervals. Automated backups of any information from machinery that is crucial for welfare assessments should also be performed at a different temporal frequency from backups of the assessment outputs themselves.

• Data Security and Cyber-physical Risks

Modern zoos aim to enhance animal welfare by acquiring data from non-invasive sensors located in exhibit enclosures and through animal tracking to gauge the well-being of individuals and species at the population level. Having access to accurate information about an animal's physical health, social dynamics, or activity patterns assists substantive and timely decision-making regarding prevention or remediation activities (V. Congdon et al., 2022).

The preservation of data security and protection against unauthorized access and cyber-physical risks is a fundamental challenge for any AI-driven health-monitoring initiative. The acquisition, transmission, and recording of biological signals, which will be used to assess an animal's welfare, giving rise to security concerns that need to be properly managed. Establishing a clear plan for maintaining the protection of a zoo's IT infrastructure is an essential step for addressing these concerns. Security still may be compromised, however, by well-intentioned people who become aware of a monitoring system unknown to management and then modify or destroy it. The development of incident-response mechanisms to detect, evaluate, communicate, and mitigate violations can help establish response measures as an additional layer to securing the system.

Future Directions

Zoos and aquariums recognizing that data-driven animal care leads to evidence-based decision-making characterized as 'intelligent animal care'. Reflects a shift from traditional methods relying on informal observations and anecdotal evidence, to more objective approaches based on systematic documentation of body condition and behaviour. Such data collection requires a certain minimal level of technology where recorded information can be manually retrieved or passively collected. Machine learning has demonstrated the capability of obtaining knowledge from unlabelled data efficiently in many fields and can therefore potentially be applied in the zoo sector. Proposed AI-driven health monitoring system enables collection of telemetry data describes such applications of AI, supporting within-zoo and global animal care (V. Congdon et al., 2022).

Zoo animals in need of urgent support, prevention and intervention time critical. Even with extensive monitoring welfare remains uncertain, certain animals monitored intensively may have historically poor welfare, while 'heavily neglected' also observed undetected. Selected animal welfare indicators useful to support informed opinions on animal welfare, associated metrics provide quantification agreed clarify welfare state. Indicator systems help focus attention on specific welfare aspects during changing conditions, gradual shifts in welfare identify improving situation.

Conclusion

The Smart Zoo will fundamentally transform captive-animal welfare by introducing autonomous, AI—driven health monitoring to the zoo environment. Automated monitoring, involving sensors and machine learning, allows animal welfare to be systematically measured over time. The Smart Zoo addresses critical monitoring gaps in zoological practice, enabling timely interventions in emergencies, sudden episodic events, inconspicuous gradual changes, and complex multi-species ecosocial systems. It proposes a low-cost approach, building on existing telemetry infrastructure and open-source AI tools, to incentivise adoption during economic downturns. Introducing such technology presents a range of theoretical, technical, and ethical challenges.

The long-term goal is a Standard Operating Procedure encompassing all aspects of welfare monitoring that permits fine-grained measurement of on-going welfare conditions and assurance of ethical treatment. The immediate vision is a preliminary species-specific Minimum Viable Product for monitoring the welfare of a single solitary species. Empirical studies executed at Carnegie Mellone University have demonstrated feasibility in monitoring two welfare domains, characterising the maturity of investment decisions with a preliminary Positioning Statement, and establishing the joint interdisciplinary framework for collaboration.

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