

Digital Transformation in Modern Zoos: Merging Technology, Nature-Based Environments and Ethical Principles

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Abstract Contemporary zoos are redefining their role in animal welfare and biodiversity conservation by integrating emerging technologies with nature-based designs and ethical care practices. Grounded in policy milestones like The Convention on International Trade in Endangered Species, 1973 and The Convention on Biological Diversity, 1992, these institutions address ecological challenges with innovative solutions while maintaining their focus on preserving biodiversity and ethical animal care.

This paper discusses the evolving nature of the zoo in relation to policy change requirements and examines how modern zoos incorporate digital technologies into their operations, integrating advanced monitoring systems and automated welfare assessment tools, while retaining nature-based habitat designs. Advanced technologies allow zoos to create tailored care strategies for animals, where enrichment designs and habitat characteristics align with species-specific needs. However, we identify challenges in standardising technology adoption across institutions and maintaining the balance between digital innovation and naturalistic care approaches.

By examining current practices, we show that successful technology implementation depends on careful alignment with ethical principles that prioritise animal autonomy and environmental integrity. The adoption of technology in zoos underscores their transformative role within the built environment. The most effective zoo operations integrate technological capabilities with nature-based design principles, creating environments where digital monitoring enhances rather than replaces natural behavioral patterns. This integration proves essential for zoos to fulfill their commitment to conservation while ensuring that animal welfare remains paramount. This article contributes to understanding how zoological institutions leverage technological innovation to advance biodiversity conservation without compromising the ecological and ethical foundations of species care.

Keywords: Biodiversity Conservation, Digital Zoo Technologies, Nature-Based Design, AI-Assisted Conservation

1 Introduction

Modern zoos have evolved from private collections of exotic animals to sophisticated conservation centers that integrate cutting-edge technology with ethical animal care [1]. This transformation has been driven by mounting global biodiversity pressures and the recognition that traditional conservation approaches alone cannot address the scale of the contemporary biodiversity crisis [2]. Central to this evolution has been a shift in how animal welfare is monitored, assessed, and managed within captive environments [3], [4]. Where zoo animal monitoring once relied primarily on periodic observations and assessments, today's institutions increasingly deploy sophisticated digital technologies that provide continuous, objective, and species-specific insights into animal well-being [5], [6]. This technological transformation encompasses everything from CCTV and camera traps to wearable sensors and AI-powered behavioural analysis systems, including emerging platforms such as the open-source ZooMonitor application [7]. These digital tools now complement rather than replace traditional evaluation methods, creating hybrid monitoring approaches that leverage both technological precision and human expertise. However, this technological integration raises critical questions about the balance between digital innovation and naturalistic care [5], [8]. As zoos adopt increasingly sophisticated monitoring systems, they must navigate complex ethical considerations about animal autonomy, environmental authenticity, and the potential for technology to either enhance or compromise ecological integrity of captive habitats [9].

This paper examines how contemporary zoos are navigating these technological and ethical complexities while fulfilling their expanded conservation mandates. We trace the historical evolution of zoo practices from entertainment-focused institutions to conservation-driven ecosystems. We explore the current landscape of digital monitoring technologies, examining both their potential to enhance animal welfare and the ethical imperatives that must guide their implementation. Through this, we show how the integration of AI-assisted monitoring, habitat replication technologies, and species-specific care protocols enables modern zoos to function as adaptive conservation hubs that balance technological innovation with ecological authenticity and ethical animal care. We conclude that successful technology integration in zoo environments depends not merely on the sophistication of digital tools, but on their thoughtful alignment with nature-based design principles and conservation objectives [3], [10], [11]. As zoos continue to implement varying levels of digital technology support, understanding these systems integration challenges becomes crucial for ensuring that technological advances genuinely enhance not compromise animal welfare and conservation outcomes.

2 Historical Foundations, Welfare Reforms & Policy Milestones

Contemporary zoos prioritise biodiversity conservation, animal welfare, and public education [12]. This modern perspective developed as zoos responded to global policy change and as public service operations recognised their critical role in assisting worldwide conservation programs, safeguarding species made vulnerable by habitat loss, climate change effects, and human behaviour's environmental impact. Zoos began to shift

their emphasis from entertainment-focused institutions to the conservation of endangered species and wildlife in the 1970s and 1980s [12].

The development of international policy frameworks fundamentally transformed zoo operations through a series of interconnected agreements and strategies. The Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES, 1973) [13], created the first comprehensive system for controlling trade in endangered species and establishing ethical sourcing standards. CITES implemented a three-tier system for classifying species according to their conservation status: Appendix I prohibits international commerce in critically endangered species such as primates and big cats, Appendix II permits limited trade with monitoring for species at risk of population decline, and Appendix III lists species protected by specific countries requiring national law compliance and trade supervision. This framework was complemented by the International Union for Conservation of Nature's (IUCN) Red List of Threatened Species in 1974 [14], which provided a systematic framework for conservation status classification that guides zoo breeding programs for critically endangered species.

The momentum for comprehensive biodiversity protection accelerated significantly with the Convention on Biological Diversity [15], signed at the Earth Summit in Rio de Janeiro in 1992. This agreement became a pivotal milestone requiring zoos to actively support species protection and habitat restoration through ex-situ conservation mandates and reintroduction efforts. Building directly upon this foundation, the World Association of Zoos and Aquariums (WAZA) [16], in collaboration with IUCN, published the first World Zoo Conservation Strategy in 1993, declaring that modern zoos must commit to species and wildlife conservation as 'species, habitats, and ecosystems' face extinction threats across the world [17]. This strategy marked the adoption of "Captivity for Conservation" as a slogan for modern zoos. The biodiversity protection framework continued to evolve through the Convention on Biological Diversity's 2010 Biodiversity Target established in 2002, followed by the Strategic Plan for Biodiversity 2011-2020, and the Aichi Biodiversity Targets in 2010. The World Zoo and Aquarium Conservation Strategy (WZACS), developed in 2005, further refined these principles by establishing specific standards for species sustainability and ethical enrichment, emphasising species-centred systems that provide mental stimulation, behavioural autonomy, and wild behaviour replication in captive environments. The policy evolution culminated with the Intergovernmental Science Policy Platform on Biodiversity and Ecosystem Services (IPBES) analysis in 2012 [18], which examined current trends and future biodiversity prospects while emphasising the importance of integrated cooperation among governments, researchers, conservation organisations, and the public in addressing the biodiversity crisis.

Contemporary zoo governance now operates within this comprehensive policy framework through sophisticated integration of conservation science and welfare protocols. Modern zoos implement species-specific welfare protocols, AI-assisted monitoring, and transdisciplinary ecological techniques to fulfil their conservation commitments, with biodiversity protection their primary responsibility [11]. These policy reforms have established zoos' ethical obligation to adopt long-term sustainability strategies for biodiversity conservation [19]. International research networks increasingly incorporate artificial intelligence for welfare analysis with cross-institutional data

exchange [6], while hybrid conservation techniques now combine zoo-based genetic diversity stabilisation with partnerships with protected reserves [20]. Rather than focusing primarily on public exhibition, sustainable breeding programs now prioritise long-term genetic stability to support species restoration efforts that extend beyond education and engagement. These coordinated policy structures ensure that zoological institutions operate as conservation-driven ecosystems, with governance structures that align with global biodiversity initiatives and welfare standards while supporting species restoration, ethical sourcing, and biodiversity protection as strategic priorities [21].

3 The Evolution of Modern Zoos

From their early beginnings as privately owned collections of exotic and confined animals displayed as a symbol of status, royalty, riches, or connections in the 18th and 19th centuries, zoological parks emerged with an emphasis on scientific research; animal welfare concerns, however, remained secondary [22]. Small cages were utilised to better showcase the animals to a public audience, but the animals frequently displayed stress-related behaviours because there was little behavioural enrichment, leading to a succession of false assumptions about what was 'normal' conduct. Breeding or reintroduction initiatives were uncommon because conservation was not a priority [23]. Despite these constraints, early zoological parks laid the framework for comparative anatomy research, species documentation, and captive breeding trials, all of which influenced ethical considerations in modern zoo administration.

Scientific research highlighted the need for ecological replication, species-specific well-being, and behavioural enrichment [24]. Enclosures evolved from sterile displays to naturalistic landscape-style built designs replicating natural biological environments (nature-based designs). Behavioural enrichment strategies were designed to ensure animals had access to stimuli that encouraged autonomous activity and cognitive engagement [25]. Ecosystem-based conservation techniques then reduced the need for artificial behavioural changes.

The modern, mostly Western Zoo serves as a multi-faceted conservation centre, combining species protection, genetic diversity preservation, and ecological rehabilitation alongside traditional education and research programs [6], [26] While not available in all zoos, digital transformation can improve conservation strategies by providing digital and/or AI-assisted monitoring, non-invasive welfare assessments, habitat replication models, and built environments that refine ethical care methodologies [27].

By enhancing inter-institutional cooperation between zoos, conservation organisations, and field researchers, partnerships with wildlife reserves advocate for species raised in captivity to be released into ecologically sustainable environments. CBD regulations preserve biodiversity preservation as a basic responsibility of modern zoos, ensuring welfare standards and digital innovation support species restoration goals [28].

These changes had a significant impact on the evolution of the modern zoo. First, we witness the changes in design of the zoo as a built environment. The habitats for each species are redesigned to replicate their traditional 'nature-based' living areas, meaning enclosures imitate natural surroundings. Second, technology-driven

conservation provides real-time species tracking and welfare evaluations that identify any differences in behaviour and welfare, such as appetite, fighting within or between species, or changes in the well-being of ageing animals [29], [30], [31]. Third, multi-disciplinary collaborations increase as zoos, universities, and environmental organisations share knowledge and open-access resources and systems [28], [32]. This level of integration means that zoos actively promote global biodiversity conservation efforts while also serving as protected areas for species well-being [29].

4 Technologies for Monitoring and AI-Assisted Conservation

The integration of digital technologies, including CCTV, camera traps, and specialised software [7], has enabled more comprehensive and objective monitoring of animal behavior and welfare [19]. Current evolution of monitoring technology has ensured the cameras are turned onto the animals, where earlier monitoring focused more on the safety of the keepers when entering enclosures to clean, add food, medication etc. There have been advances in ensuring staff safety, enabling more time for enrichment and play with animals. For example in Fig.1 and Fig. 2, as part of the regular daily routine, we see the chimpanzees move into the outside area while the keepers close off and change their inside environment, refreshing bedding, cleaning and adding different food piles and activation activities. Meanwhile the chimpanzees are shifting around outside, looking in through the windows, even pushing each other aside, to see where the keepers are placing the food etc. so they can be first in when they return inside.



Fig. 1. and Fig. 2. Chimpanzees peer through the windows, often even pushing each other out of the way, to see where new food is being placed by the keepers (Source: authors own work).

Regardless, adoption of these monitoring technologies varies across institutions, with many zoos still primarily relying on traditional inspection methods [3]. This disparity suggests a need for standardised implementation guidelines and support for technology adoption across the zoo community. However, it may not just be a case of replacing one system with another. The emergence of integrated monitoring approaches, combining keeper assessments with digital tools, has shown promising results in providing more complete welfare assessments [33]. Focal observations and 24-hour interval

monitoring provide a more complete picture of animal welfare [33] including behavioral, health, and social parameters [34]. The development of specialised tools like the Animal Welfare Assessment Grid (AWAG) [27] and ZooMonitor [7] represents significant progress in standardising welfare assessment methods [9], [30]. These tools have enabled more targeted interventions and personalised care strategies. Hybrid approaches leverage both the systematic nature of digital monitoring and the valuable insights of experienced keepers, producing a nuanced understanding of animal welfare states [3], [6].

AI-powered monitoring systems can support species-specific conservation initiatives while also integrating several dynamics simultaneously, including automating the tracking of species-specific behaviours over time. Monitoring technologies can allow keepers to employ a variety of non-invasive physiological tests as needed for each individual animal, reducing the need for human intervention while improving welfare outcomes [35], [36]. This shift allows keepers to then focus their interactions more on play enrichment rather than welfare assessment. Machine learning algorithms, with the aid of habitat replication models, can inform the design of evolutionary habitats based on ecological trends observed in natural ecosystems, as animals in the wild adapt to changing conditions caused by habitat loss, climate change, population growth, predators, and so on. These types of digital transformations can improve biodiversity preservation by increasing real-time monitoring capacities to ensure that welfare strategies adapt to needs, as well as integrating global conservation databases to share knowledge and support species sustainability (IUCN, 1974).

Among the technological breakthroughs are AI-powered tracking devices that enable non-invasive behavioural assessments for improved well-being analysis [6]. Automated habitat calibration adjusts enclosure parameters (such as humidity, temperature, and substrate density) to resemble those found in the wild [31], [37], [38], [39]. Machine learning methods are used in predictive welfare modelling to maximise species enrichment density [40], [41]. Incorporating technology-driven conservation into zoo sustainability models ensures that welfare improvements and biodiversity preservation complement rather than compete [24]. For example, the San Diego Zoo Wildlife Alliance implements Genetic Diversity & Conservation Policy in building frozen genome biobanks for its Genetic Diversity Monitoring program. This aims to save viable genetic material from endangered animals to better understand extinction risk, management, and conservation interventions for future conservation and biodiversity efforts [42]. To strengthen the genetic resilience of wild populations, the zoo collaborates with international reserves and breeding programs through cross-institutional ties to ensure that species survival is consistent and aligns with long-term ecological aims. Chester Zoo, acting on biodiversity preservation mandates, collaborates with global conservation databases and delivers species welfare indicators—for example, noting the significance of the social group structure in development for captive chimpanzees—to international research institutions via Automated Data Sharing for Worldwide Conservation Networks [43] upholding the ethical use of technology in biodiversity governance [23].

5 Ethical Imperatives in Zoo Design and Operations

While technological advancements may benefit conservation efforts, there are numerous ethical challenges that can arise when digital interventions dominate naturalistic behaviours or ecosystems or compromise the ecological integrity of the overall operational scenarios [21], [44], [45]. Ethical zoos must maintain a system of balanced habitat configurations, where the technology complements and supports the natural features of the environment, rather than replacing human interactions which may benefit the animals and the animal-human bond, as developed with the keepers.

In addition, a major challenge is to strengthen species autonomy frameworks while avoiding excessive digital exposure that affects behavioural ecology, such as the use of artificial lighting, sensor-activated systems that disrupt the natural environment, streaming activities, and so on. Further, any AI-driven conservation techniques must be evaluated to ensure that they are consistent with nature-based ecosystem dynamics and environments, such as those in which animals would live in their natural habitat [45]. By combining ethical principles with digital advances, modern zoos can adhere to and achieve biodiversity conservation goals while also ensuring that technological tools improve rather than disturb the natural ecological balance for each species [9].

Although complex enrichment is thought to be a reliable and effective technique for improving animal welfare, its effectiveness varies depending on each animal's inclination for novelty [24]. Current research on animal welfare in captivity stresses consideration of individual animals' needs, cultural customs, and mental and emotional well-being. Studies highlight the value of collective learning for enhanced care and welfare [43], and the need to acknowledge captive animals as coming from their own social and cultural ways of being [29]. The concept of freedom, and its implementation, calls for comparative research into the life cycles of captive and wild animals. Implementation of habitat replication modelling may narrow the focus, missing current broader evolving social and cultural needs of the situated set of captive animals [8].

6 Discussion: Strategies & Species-Centred Innovation

To maximise species-centred care, contemporary well-resourced zoos operate as multidimensional conservation hubs that blend cutting-edge welfare measures, AI- assisted or digitally enhanced behavioural tracking, and habitat replication models. Contemporary zoos are tasked with balancing biodiversity issues, ecological ethics, and technology influences on zoological activities [46].

Digital behavioural assessments have transformed zoo management and species-specific treatments. Contemporary zoos leverage AI-powered systems, useful to investigate social connections and mobility patterns and detect welfare difficulties [31], as well as to optimise enrichment operations. Technologies such as infrared behavioural scans can identify stress signals [27]. Additionally, automated health evaluations can track physiological parameters such as locomotion stability and dietary changes [6]. Supplementing observational data in this way broadens the evidence base for decisions about animal well-being [7], [11], [33], [34]. Further, digital technology systems

provide cross-institutional monitoring networks to support endangered species management techniques that strengthen biodiversity conservation efforts [23].

Adaptive ecosystem modelling is now represented in modern zoo enclosures, ensuring that animals thrive in environments that closely resemble their nature-based habitats [24], [27], [37], [45]. Climate-adaptive enclosures, which modify temperature, humidity, and seasonal cycles in response to natural biological variables, are one example of such adaptation. Further, there is an emphasis on species-specific locomotor behaviours, with terrain reconstruction mimicking natural topographical variations [7], [41] and sensory enrichment systems employing bioacoustics stimulation and realistic soundscapes to reduce artificial stressors [10]. Incorporating technology frameworks into enclosure designs can help to mitigate the possibly harmful effects of captivity while also ensuring biodiversity conservation goals are met [28], [46].

While digital technologies facilitate welfare tracking and habitat duplication, zoos must maintain ethical enrichment standards that prioritise species autonomy and environmental sustainability. Ethical enrichment models include, for example, natural foraging techniques that use sensor-triggered feeding stations to mimic wild food patterns [47] and cognitive stimulation frameworks that use dynamic environmental changes to reduce boredom-induced stereotypic behaviours [48]. Minimal intervention tracking ensures technology promotes welfare optimisation rather than dictating behavioural training [26], [41].

By adhering to species-centred ethical criteria, zoos ensure that biodiversity protection is interwoven in technology interventions, avoiding artificial manipulation while ensuring long-term ecological stability and technological advancements are consistent with species sustainability regulations [39].

Effective conservation strategies include AI-assisted reintroduction programmes and improving habitat selection for endangered species release projects [49]. Cross-institutional genetic diversity stability entails merging zoo-managed breeding programmes with wild population genetic models [50]. Hybrid conservation collaborations enable zoos to engage with protected reserve networks on ecosystem restoration projects [32]. These developments strengthen zoological institutions' involvement in global conservation frameworks by protecting species genetic integrity while reducing captivity-induced behavioural alterations [23].

7 Limitations and Future Work

With limited space, multiple aspects that impact the daily lives of the animals and keepers have not been included. Future work would include for example, addressing improving the efficiency of remote connection data collection and analysis systems, with alert notifications signalling where urgent attention is required. Another major factor would include the impact which visitor engagement has on multiple aspects of quality of life in zoos. Some animals 'perform' for visitors and appear to enjoy the engagement. However, monitoring has captured intimidating behaviour from visitors towards animals, producing changes such as increasing the distance between visitors and the animals inside the enclosures, adding foliage for privacy or sound barriers etc. The

addition of case study examples, particularly demonstrating examples of deployment would enrich understanding for the reader.

8 Conclusion

The application of contemporary AI-assisted behavioural tracking, habitat replication technologies, and ethical enrichment strategies ensures that contemporary zoos function as adaptive conservation hubs rather than traditional exhibition spaces by addressing policy requirements. By embedding biodiversity conservation mandates within digital transformation methodologies, zoos uphold species sustainability objectives, ensuring welfare interventions complement rather than override natural ecological principles. Biodiversity conservation and natural environments remain a key prerogative, ensuring these as a focus with the use of digital tracking methodologies, ethical enrichment models, and conservation strategies. With the zoo community still transitioning into varying levels of technology adoption and implementation, future efforts would benefit from addressing implementation challenges while maintaining the benefits of both traditional and modern monitoring approaches. Future work includes addressing effective scalability of these hybrid approaches and must include the impact that visitor interactions play in animal welfare considerations within a systems thinking approach.

9 References

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