University of Southampton

Faculty of Arts and Humanities

Winchester School of Art

Robot Animals

To design and make

by

Yijie Gao

Thesis for the degree of Design

September of 2025 submission

University of Southampton

<u>Abstract</u>

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<u>Doctor of Philosophy</u>

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This study explores the potential of robotic animal companions in human-robot interaction (HRI) and their effects on emotional well-being. With increasing urbanization, traditional pet ownership is becoming less feasible, necessitating alternative companionship solutions. Additionally, advancements in robotics, electronic technology, and the growing social acceptance of virtual characters in human relationships have made it technically feasible to develop more biomimetic, autonomous, and long-term relationship-oriented robotic animals.

A mixed-methods approach was employed, focusing on robotic animal development, iterative redesign, public demonstrations, and user feedback-driven improvements. The study emphasized the importance of animal behavior, physiology, and human-animal relationships in replicating meaningful interactions in human-robot

relationships. Controlled experiments and qualitative interviews were conducted to analyze users' psychological and physiological responses to bio-inspired robotic animals.

The study successfully developed interactive robotic animals with both practical and theoretical innovations in design, materials, control systems, and interaction modalities. Notably, the robotic animals featured an autonomous control system, a model of human-animal relationships, and novel mechanisms for animal-inspired vocalizations and tactile perception through custom-designed touch sensors. Results indicate that interacting with these robotic animals significantly reduced stress levels and increased positive emotional engagement. Participants exhibited behaviors similar to those seen in human-animal interactions.

These findings highlight the potential of bio-inspired robotic animals as effective emotional support tools. The study contributes to the design of future HRI systems and suggests applications in therapeutic and assistive robotics. The practical implementation of robotic animals provided both creators and users with a tangible and immersive experience, reinforcing the significance of these developments for the future of robotic animal research. The accumulated experiences and theoretical insights gained from this study are crucial for advancing the field of robotic animal development.

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https://youtu.be/0nuEBfoXNqM

https://devpost.com/software/gua

Research Thesis: Declaration of Authorship

Print name: Yijie Gao

Title of thesis: Robot Animals

I declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
2. Where I have consulted the published work of others, this is always clearly attributed;
3. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
4. I have acknowledged all main sources of help;
5. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;

Signature: .... Date:........................

Acknowledgements

I would first like to thank myself for bravely stepping into the unfamiliar field of robotics, turning a once-vague fascination into meaningful research.

My deepest gratitude goes to my supervisors, Seth and Vanissa, for giving me the opportunity and support to shape abstract interests into something tangible.

When I look at robotic animals, I can never forget all the animals—whether lifelong companions or fleeting encounters. They were the crabs that never made it to the restaurant kitchen, the bullfrogs in supermarket tanks, the squirrel I raised from birth to old age, the stray dogs, fierce little cats, rescued magpies, and swift turtles. With lives long and short, they wrapped me in love, teaching me how to care for life and see the world through their eyes.

In this journey, Anne reassured me that my fascination with animals wasn't strange but necessary—even if my goal was to create their "substitutes."

I am also grateful to SETA (Southampton Engineering Training Association) for welcoming me into the world of mechatronics, filling gaps in my knowledge, and building my confidence in mechanics and electronics.

A heartfelt thanks to my Goldfish team friends, whose dedication turned GUA from a fragile prototype into a fully-fledged robotic project with custom circuits. Our collaboration continues, and I cherish the journey.

I deeply appreciate my family for their unwavering support, giving me the time, love, and stability to pursue my research. Even my grandfather follows my work closely, a testament to their genuine care and understanding.

Finally, I thank the University of Southampton, FAH, and WSA for their immense freedom and support, enabling my interdisciplinary research.

Of course, I cannot forget GUA—the life I created. Together, we will push bio-inspired robotic animals into new frontiers.

Definitions and Abbreviations

PCB .... A Printed Circuit Board (PCB) is a board made of insulating material that mechanically supports and electrically connects electronic components using conductive pathways, tracks, or signal traces etched from copper sheets. PCBs are essential in modern electronics, providing a compact and organized platform for electronic circuits. They are widely used in consumer electronics, industrial machines, medical devices, and robotic systems.

HRI .... Human-Robot Interaction (HRI) is the interdisciplinary study of interactions between humans and robots. It involves designing, modeling, and analyzing how robots perceive, interpret, and respond to human behaviors and commands. HRI aims to enhance communication, collaboration, and cohabitation between humans and robots in various domains, including healthcare, industrial automation, and social robotics.

AAT .... Animal-Assisted Therapy (AAT) is a therapeutic intervention that incorporates animals into the treatment process to improve physical, emotional, cognitive, and social well-being. AAT is guided by healthcare professionals and involves structured interactions with animals such as dogs, horses, or robotic animals to aid individuals with mental health issues, disabilities, or medical conditions.

HCI .... Human-Computer Interaction Human-Computer Interaction

GUA.................................The robot animal(s) I designed and made

Chapter 1 Introduction and Research Questions

This chapter is where the whole adventure begins. It's where I try to explain why building robotic animals even matters (and why I care so much). It introduces the five central research questions, but also the real questions behind the questions—like what makes something feel alive, or why people get attached to things that don't breathe.

1.1 What is Robot animal

Robotic animals are mechanical creations that mimic the appearance, behaviour, and perception of real animals.

In a broad sense, animal robots include any robotic system inspired by animals, from biologically inspired machines used for scientific exploration to artistic expressions in media and entertainment whose main purpose is to interact with humans. Academically, robot animals usually refer to systems designed to replicate specific aspects of animal movements, behaviours, or physiology, which often require the integration of electronic sensors to form a "black box" with comprehensive biomimetic perception capabilities.

Narrowing the scope, robot animal research focuses on autonomous robots that can interact with humans while exhibiting behaviours and perceptions similar to real animals. These robots use advances in artificial intelligence, sensing technology, and bionics to respond to stimuli in a way that evokes the lifelike qualities of animals.

This project didn't start because I wanted to "solve a problem." It started because I had a strange feeling that some machines might be more alive than they look. Maybe not alive like squirrels or frogs (though I've lived with both), but alive in a softer, quieter way—like puppets, or kites, or toys that seem to wait for you.

A big part of this comes from animism, which says that objects—if loved, touched, named—might hold spirit. It's not a new idea; it's old and gentle, like the way a child whispers to a rock or a grandmother puts fruit out for a wooden fox. In this way of seeing, a robotic animal doesn't have to prove it's alive. It just has to be loved in the right way. There's also something called the biophilia hypothesis , which says people feel better when they're close to animals and plants. But in cities, where the air smells like metal and there's no room for cows or crickets, we have to make do. So maybe a robot, if it blinks and responds and leans in when you speak, can remind you of the world outside the walls. Not as a trick, but as a kindness.

And lately, machines have been catching up. They glow now. They sigh. They curl their ears, or at least pretend to. Technology has changed, and people have changed with it. A robot used to be something you saw in a factory; now it's something your niece sleeps next to. And no one thinks that's strange.

Of course, this also means we need to think about what we owe to these beings. Not because they're legal persons (they're not), but because *we* are the kind of creatures who get attached. People cry when Tamagotchis die. They talk to toaster ovens. And they get furious if their robot dog ignores them. So there are real ethical questions here—about care, attention, and where to draw the line between pretending and believing.

This project doesn't try to fix that. But it does try to stay very close to it. To the edge where wires start to wag like tails, and people start to say, "I know it's not alive, but still..."

From the perspective of humanities and arts, this is the inheritance of humans' continuous creation of "animals" with various materials for thousands of years. People have gone from stone and mud to wool and gold and silver, from sculptures to automata, from stuffed toys to puppets, and now we have a more dynamic medium - electricity as energy, sensors as five senses, flexible robot bodies and chips that carry more brain power. I am still an artist who carves the beautiful animal images in my mind.

1.2 Why we need Robot Animal

Robotic animals offer a refreshing alternative for human-animal interactions, particularly in the face of modern urban challenges. Unlike their real-life counterparts—who demand time, space, and plenty of resources to thrive—robotic animals are easy to maintain and controllable (though they can also be designed with unpredictable behaviours to reflect the quirks and individuality of real animals), and effortlessly adapt to the fast-paced city lifestyle. As McBride and Olivier (2004) aptly highlight, robotic pets remove worries about feeding schedules, daily walks, or unexpected vet bills, making them a stress-free option for busy professionals or those living in tight spaces. Moreover, these high-tech companions excel in environments where hygiene and safety are non-negotiable, such as hospitals or densely populated urban centres, where real animals might simply be off-limits.

Giddings (2021) takes this idea a step further, diving into the cultural and emotional nuances of robotic animals. He points out their unique ability to transcend the limitations of real-world species, offering imaginative interactions with creatures that are extinct, fantastical, or even entirely invented. Think of it this way: robotic animals aren't just pets—they're portals into a creative relationship with "animal-like" beings, bridging reality and fantasy. Whether you're befriending a robot dragon in a downtown apartment or a mechanical dodo in a hospital room, these interactions foster creativity and companionship in ways that real animals cannot, especially in the constraints of urban life.

But robotic animals are not just about companionship—they shine in healthcare and education, addressing needs in ways traditional solutions often can't. For instance, they provide emotional comfort to individuals with mental health challenges. Unlike therapy dogs, which can be unpredictable and are limited in availability, robotic animals are always on-call and entirely controllable. In settings where hygiene is critical, such as hospitals or care facilities, these robots match the cleanliness of medical devices, removing barriers that keep live animals out (Shibata, 2012; Wada and Shibata, 2008).

In education, robotic animals offer children a hands-on way to learn about animal behaviour, respect for animal cognition, and biological processes—all without the ethical or safety concerns that come with live animals. They can precisely simulate behaviours and life cycles, providing immersive learning experiences in a safe, controlled environment (Bers et al., 2002; Breazeal, 2003). By combining lifelike interaction with scientific accuracy, robotic animals open doors to teaching methods that are both fascinating and ethically sound.

Robotic animals also shine in the vastness and loneliness of space, and their potential may be as limitless as the universe itself. Imagine: astronauts trapped in a tin can traveling through the universe, missing their pets or even just anything alive. Robotic animals are the ultimate space companions. Unlike traditional therapy animals (which, let's face it, aren't practical in zero gravity or fragile space capsules filled with delicate instruments), they can display animal-like interactive behaviours in a customized way, and this sense of reliability and intimacy is doubly true when such interactive systems are attached to robots that already have the ability to assist. These bots are as clean as medical instruments and as interactive as the iconic Benben, the robotic dog from *The Wandering Earth 2*. Just like how audiences adored Benben for its quirky personality and undeniable charm, these robots could win over astronauts with their emotional intelligence and playful behaviours.

Figure 1 Benben Robot Dog in movie *The Wandering Earth 2.*

Studies have shown that bio-inspired robots with social capabilities are a game-changer for space missions. Breazeal (2003) highlights how robots designed for human-like interactions can evoke trust and foster emotional bonds. Similarly, Fujita and Ishiguro (2023) demonstrated that robotic animals with animal-like behaviours provide much-needed psychological relief for astronauts in confined environments. These bots don’t stop at wagging their metaphorical tails—they also improve team dynamics and trust, according to Shibata and Wada (2022). Imagine a robot that’s part pet, exploration partner, or even a saviour, turning a tight team of “just humans and a tough challenge” into a more organic pioneering team. Chinese astronaut Wang Haoze recently demonstrated a social robot developed by Harbin Institute of Technology, under the leadership of Zhang (2025). The robot, designed for interactive engagement in the space station, illustrates how social robots can support astronauts’ mental well-being by mitigating isolation in confined environments.

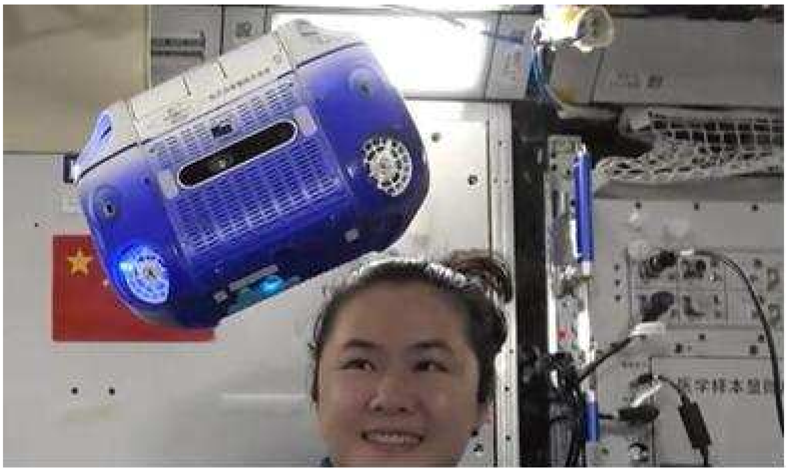

Figure 2 Robot Xiaohang

There are two main aspects of robot animals being able to participate in human society.

How to make them and how people get along with them. These two questions will be asked repeatedly throughout the study and will be tried to be answered through practice, thinking, observation, integration and trying different techniques.

The design and research of robotic animals is an exciting and interesting branch in the field of robotics. It can not only realize people's current pursuit of building a harmonious future with beautiful artificial animal images, as in the world of Pokémon, but also promote the development of robots with more autonomy and vitality. Robots animals participate extensively and organically in human life needs to have rich emotions, autonomous perception, animal-like appearance and movement capabilities, and the ability to establish long-term emotional relationships with people and other creatures (included other animals and robots). The hidden technical needs involve bionic robotics, cognitive robotics, sensor and perception system research, and autonomous system design research, as well as more macro research directions such as robot ethics, robot regulations, Human Robot Interaction (HRI), and human-machine collaboration.

The development of robots is a highly interdisciplinary and integrated research field. In previous studies, experts in a certain field, such as researchers in electromechanical engineering or computers, led the design of the project (Progress in Biomedical Engineering, 2024).

1.3 Research Questions

1.3.1 The Narrow Relationship Between Robotic Animals and Humans

To create robotic animals that are meaningful and engaging to humans, the following questions arise:

Interactivity: How can robotic animals be designed to facilitate dynamic, emotionally resonant interactions with humans?

Memory and Specificity: What role does memory play in making robotic animals capable of recognizing individual humans and adapting their behaviour accordingly?

Human Understanding of Animal Relationships: How can the design of robotic animals enrich human understanding of real animal behaviour and relationships?

Special Characteristics: What unique features of robotic animals could enhance their distinctiveness and appeal in human-robot interactions?

These questions guide the exploration of creating robotic animals that are not just functional but capable of forming long-term emotional bonds, drawing parallels with human-animal relationships.

1.3.2 The Relationship Between Robotic Animals and Human Society

The integration of robotic animals into broader social contexts involves addressing the following:

Suitable Environments: What environments are most conducive to the acceptance and utility of robotic animals (e.g., homes, public spaces, farms)?

Legal and Ethical Considerations: What legal frameworks and ethical guidelines are needed to regulate the production, use, and potential societal impacts of robotic animals?

Technical Support: What systems of maintenance, energy supply, and infrastructure are required to ensure the long-term viability of robotic animals?

Addressing these questions emphasizes the interdisciplinary collaboration required to embed robotic animals into society safely and sustainably.

1.3.3 Development Challenges

The creation of robotic animals necessitates innovation across various technical fields:

Structural Design: How can the mechanical and electronic structures of robotic animals achieve an optimal balance between durability and biological realism?

Systemic Innovations: What new systems can be developed to integrate perception, cognition, and behaviour in ways that mimic animal intelligence?

These challenges highlight the need for a seamless integration of engineering, biology, and system design to make robotic animals functional and lifelike.

1.3.4 Enhancing Specific Capabilities of Robotic Animals

To achieve higher performance and realism, robotic animals must excel in certain areas:

Cognitive Abilities: How can robotic animals process environmental stimuli to exhibit complex, context-aware behaviours?

Sensor Integration and Data Processing: What advancements in sensors and information fusion are necessary to improve perception and interaction capabilities?

Customization and Aesthetic Appeal: How can the appearance and behaviour of robotic animals be personalized to suit diverse human preferences?

Biomimetic Motion: What innovations in bio-inspired robotics can improve the motion fidelity and expressiveness of robotic animals?

This research aims to enhance the functional and aesthetic qualities of robotic animals, making them more relatable and effective in human contexts.

1.3.5 Building Emotional Impact Through Storytelling and Long-Term Engagement

The success of robotic animals also depends on their ability to evoke emotions and build relationships: The success of robotic animals also depends on their ability to evoke emotions and build relationships:

Narrative and Background Design: How can compelling backstories and personalities enhance the emotional resonance of robotic animals?

Sustained Emotional Progression: What strategies can foster long-term emotional connections between robotic animals and humans, beyond initial novelty?

Considering that robotic animals are still a rare thing (not because there are no examples, but because they haven't really entered the public's daily life—and any new invention needs both developers and society to shape it), the research questions above sound a bit too serious and theoretical. In reality, the process is full of strange and sometimes ridiculous problems. For example, how do we stop people from kicking the robots? If someone feeds it and it breaks, does that count as a warranty issue? If a robot breaks something, who's responsible for paying? Should a robotic animal bark or just ignore people if it feels threatened? How do we stop it from becoming someone's weird fantasy? Can it carry someone's memories of their dead pet? And honestly, would using real animal fur instead of fake fur make it better?

Some of these concerns are grounded in real discussions. For example, Williams (2005) highlights the ethical and behavioral challenges of integrating robots into human environments, raising questions about misuse and societal expectations. Similarly, Dang et al. (2017) explore how robotic emotion systems need to adapt to cultural differences, indirectly reflecting on how robots might be misunderstood or even misused. Meanwhile, Webb (2001) delves into the limitations of robotic systems compared to real biological behaviours, noting the complexity of replicating life-like interaction.

The technical side of these questions also has backing in the literature. For instance, Loeffler (2019) emphasizes the importance of using motion, sound, and color to create believable robotic interactions, which might also influence how people emotionally connect (or disconnect) with them. Hill et al. (2020) examine how robot personalities impact human-robot cooperation, which raises questions about whether certain personality traits—like aggression or passivity—could lead to unintended consequences. Finally, Oxley (2021) provides insights into how virtual animal interactions shape human expectations, which could help frame how people might project emotions and memories onto robotic animals.

These questions might decide if robotic animals become a long-lasting industry, like smartphones, or if they evolve into something wild and unpredictable with future tech—maybe even becoming dangerous weapons just because they're so closely tied to human life. I'll keep an eye on these possibilities and, within my abilities, aim to create robotic animals that are truly full of life.

Beyond all the practical and technical challenges, the biggest issue with robotic animals might actually be our understanding of animals themselves. After all, if we don't deeply grasp what makes animals think, act, and connect with humans, how can we ever hope to build machines that convincingly mimic these qualities? This is not just a technical question but also an invitation to reconsider the vast and complex world of real animals.

Research on human-animal relationships highlights just how intricate these bonds can be, shaped by a blend of instinct, learning, and environmental factors. Animals are far more than biological entities—they serve as emotional partners, mirrors of human behaviour, and active participants in social frameworks. For example, studies of pet ownership reveal how deeply animals influence emotional well-being and social connection (McBride, 2000). If robotic animals are to achieve similar effects, they may need to simulate trust and loyalty or inspire entirely new forms of attachment.

The cognitive and emotional depth of animals adds another layer of complexity. Livestock behaviour studies show how animals are extraordinarily sensitive to their environments—responding to subtle stimuli such as shadows, smells, and body language, which humans might easily overlook (Grandin, 2005). This hypersensitivity raises intriguing questions for robotic animal design. Should machines aim to replicate this acute perception, perhaps even exaggerate it, or would it be more practical to simplify their responses for easier human interaction?

The idea of imprinting, a behaviour famously documented in geese (Lorenz, 1935), provides further inspiration. Animals don't merely react to their surroundings—they carry the evolutionary history of their species in their instincts and interactions. Imprinting demonstrates how animals form bonds that are both instinctual and adaptive, shaped by a combination of biology and environment. If robotic animals could “imprint” on their owners—learning to adapt and respond over time—this might create bonds that feel authentic, even if they are entirely artificial. Such behaviours could blur the line between robotic and organic life, challenging our assumptions about what it means to "connect" with a machine.

These ideas aren’t just theoretical musings—they open up creative possibilities and philosophical dilemmas. For instance, should robotic animals exhibit behaviours inspired by natural instincts, like curiosity or fear, even if these instincts are simulated? Or should they represent an entirely new category of animal-like behaviour, unrestricted by evolution but still aligned with human expectations? And what about aggression? While it’s tempting to imagine robotic animals as peaceful companions, it’s worth asking whether they should—or could—be more aggressive. Who’s to say the supreme human desire for harmonious interactions with animals isn’t occasionally challenged? After all, relationships between complex species often involve competition and testing boundaries. Perhaps humans might even find satisfaction in being tested or confronted by robotic animals, echoing the dynamics of competition and challenge that are central to many interspecies relationships. This possibility opens up questions about whether robotic animals should push beyond the role of obedient companions to reflect the complexity—and sometimes unpredictability—of real animals.

Perhaps the best animal companions are not those meticulously designed by breeders, but those nurtured with love, just as in The Little Prince. It is through choosing each other that the fox became special, and it is because of your love that the rose became unique. Even a factory-farmed chicken, raised with care from the start, can become an interactive companion; a wild bear, treated kindly, may grow into a neighbor who visits from time to time. It is through the shared imagination and care of their users that robotic animals may evolve into soulful and meaningful companions.

1.4 Methods and Results: Exploring Human-Animal, Human-Robot, and Virtual Animal Relationships

1.4.1 Ethological Observation

This research begins with foundational insights from animal psychology and ethology. Observational studies, such as those discussed by Ellingsen et al. (2014), highlight how human behaviours (e.g., naming or showing affection toward animals) influence animal responses. These observations inform the design of robotic animals by emphasizing trust, reciprocity, and intuitive communication.

1.4.2 Behavioural Coding and Emotional Modelling

The system integrates behavioural coding inspired by real animals, layering primary and secondary emotions as outlined by Becker-Essner (2017). Primary emotions drive immediate, reflexive responses, while secondary emotions simulate more complex, context-dependent reactions. This hierarchical structure enhances the robot's behavioural credibility and emotional resonance.

1.4.3 Human-Robot Interaction (HRI) Testing

The design process incorporates tools like the Robot Social Attribute Scale (RoSAS) (Carpinella et al., 2017) to evaluate how users perceive the robot's warmth, competence, and emotional engagement. These structured testing methodologies ensure that robotic behaviours align with human expectations of companionship and interaction.

1.4.4 Cultural Adaptability

Building on the work of Wanick (2018), the system includes cultural adaptability testing to ensure its emotional expressions and behaviours are relatable across diverse user groups. This method helps the robot maintain broad accessibility and fosters acceptance in different social contexts.

1.4.5 Virtual Interaction Analysis

Gaming studies, such as Giddings (2015), offer insights into designing engaging and rewarding interactions. The robot's ability to adapt and personalize behaviours mirrors the mechanics used in virtual companions, creating a platform for fostering emotional connections.

1.4.6 Iterative Prototyping and Feedback

Prototypes were developed and tested in controlled environments, with iterative adjustments based on user feedback. This iterative process, informed by qualitative assessments and quantitative scales, ensured the robot's behaviours were refined to balance realism, adaptability, and reliability.

1.4.7 Cross-Disciplinary Integration

The research synthesizes insights from multiple disciplines, including psychology, robotics, and HCI. This interdisciplinary approach ensures that robotic animals are not only technically sound but also emotionally engaging and socially relevant.

1.4.8 Behaviour and System Design

This research began with countless hours of watching animals—squirrels darting about, geese waddling (and hissing), crocodiles basking in eerie stillness, turtles trudging, dogs wagging their tails, and horses flicking their ears. These observations weren't formal studies, but they offered something even better: raw inspiration. Each flick, jump, or waddle became a thread to weave into robotic behaviours, much like choreographing a show (except the performers are metal and circuits).

The robot's "brain" works on a hierarchical information processing system. Data moves through layers, where each layer plays its part in decision-making. Instead of throwing everything into one big computation (like cramming for an exam), the system uses thresholds—upper, middle, and lower—with weights to decide what really matters. The result? A robot that acts quickly and effectively without getting bogged down by unnecessary calculations (or existential crises).

The hardware is a no-frills, self-contained system. Multiple microcontroller modules (a bit like tiny team members) report to a central hub, making decisions without any internet connection or data storage. Everything happens in real time—fast, private, and surprisingly robust for something that doesn't rely on the cloud.

1.4.9 Related Systems and Case Studies

This approach isn't entirely unique—Keepon, a charming little robot designed for social interaction research, operates in much the same way (Kozima et al., 2009). Keepon keeps things simple: offline processing, real-time responses, and a focus on human connection (mainly by bobbing and gazing).

Paro, the therapeutic seal robot, takes a similar route. It uses sensors to feel touch and hear sound, responding instantly to users in care settings without ever storing or transmitting data (Shibata, 2012). Both robots prioritize privacy, reliability, and simplicity over flashy features, proving you don't need complex systems to make meaningful interactions happen.

1.4.9.1 Advantages and Limitations

This design shines in a few key areas:

• Privacy: No internet, no data storage, no problem.
• Security: No hackers here (unless they figure out how to hack offline robots).
• Easy Maintenance: No external dependencies, no messy updates, no user manuals that who is an engineer)
• Low Cost: Simple designs mean smaller budgets (and fewer headaches).
• Compact Size: Portable enough to go anywhere (even if it doesn't like to walk too far).

But it's not all rainbows:

• No Long-Term Memory: This robot forgets everything the moment it happens—so no learning from past mistakes.
• Manual Adjustments Only: Without data to analyze, improving its behaviour involves old-fashioned tinkering.

Still, for a system that prioritizes privacy, simplicity, and immediacy, this design hits the sweet spot (even if it sometimes feels like greeting with an wild raven who never know you). Inspired by both nature and practical robotics, it offers a sturdy, low-cost solution for real-world applications.

1.4.9.2 First Generation: Random Cube System with 3 Dimensional Prototype

The first generation followed a sensor-to-brain model, where raw sensory data was processed through weighted averaging to produce three key "perceptual values":

• Emotion value: Represented the robot's simulated emotional state.

• Activity level: Defined how energetically the robot would behave.

• Motivation level: Influenced goal-directed behaviour.

Behavioral outputs consisted of 27 actions categorized into 8 groups. The perceptual values acted as intermediaries to determine the appropriate behaviour group, after which a specific action within the group was randomly selected. This design introduced variability and unpredictability, making the robot's responses appear more natural and less deterministic. While functional, this generation faced limitations in scaling to more complex scenarios and maintaining long-term responsiveness.

1.4.9.3 Second Generation: Simplified Behavior and Binary Decision-Making

The second generation streamlined both behaviour design and decision-making:

• Simplified actions: The 27 actions were consolidated into 18 behaviour groups, reducing complexity while preserving versatility.

• Binary autonomy: The activity level was replaced by a binary "yes" or "no" system for determining whether the robot should act in a given context.

This simplification reduced computational overhead and allowed for faster decision-making, aligning the system more closely with the hardware's capabilities. By focusing on broader behaviour categories and using binary logic for autonomy, the robot could maintain robust responses in diverse situations while minimizing resource demands.

1.4.9.4 Third Generation: Layered Perceptual Influence and Expanded Mechanics

The third generation marked a significant leap in system sophistication, with several key advancements:

• Layered Perceptual Influence:

Emotion values were directly influenced by sensory inputs ("perceptions").

Activity levels were tied to the rate of change in perception, where rapid or extreme sensory changes triggered heightened activity.

Special behaviours were introduced for extreme sensory inputs (e.g., defensive or evasive actions), enhancing adaptability in unexpected situations.

• Expanded Behavior Library

Foundational movement actions were added to ensure effective navigation and interaction.

Special behaviours enriched the system's ability to simulate more nuanced and context-dependent responses.

• Modular and Distributed Architecture:

The system architecture was restructured into five core processing units:
Wheeled movement control module: Managed locomotion and environmental navigation.
Arm-type motion control module: Handled precise and dynamic manipulative actions.
Central brain module: Focused exclusively on decision-making and coordination.
Sensor module: Preprocessed sensory input for real-time responsiveness.
Non-mechanical output module: Generated user-oriented feedback through lights, sounds, or other communicative means.

Enhanced Mechanical Capabilities:

• Basic locomotion and arm-like manipulation were prioritized, allowing the robot to engage in more complex interactions with its environment.
• Multi-axis actuation was optimized for smoother, more lifelike movements.

Completely Offline System:

• The robot operated entirely without network connectivity, ensuring data privacy and security.
• All processing occurred in real-time, with no reliance on data storage or cloud computing.

Advantages and Limitations

This progressive evolution of the system offers distinct advantages:

• Privacy and Security: The fully offline architecture eliminates concerns about data storage and network vulnerabilities.
• Efficiency and Low Cost: Simplified logic and modular design reduce computational requirements, making the system cost-effective and energy-efficient.
• Compact and Adaptable: The lightweight architecture ensures portability and usability in diverse environments.
• Fast Response Times: The decentralized processing system allows for rapid decision-making, crucial for real-time interactions.

However, the design also has certain limitations:

• No Long-Term Memory: The absence of data storage restricts the robot from building on past interactions or learning over time.
• Limited Data-Driven Refinement: Improvements rely heavily on manual adjustment and iterative testing rather than automated feedback from usage data.

1.4.10 Insights from Games, Intelligent Toys, and Automata

1.4.10.1 Game Mechanics and Playful Interactions

The design of robotic animals draws heavily on the role of play in fostering emotional connections. Giddings (2023) emphasizes how game mechanics create spaces for experimentation and exploration, offering opportunities to build meaningful interactions through adaptive and responsive systems (pp. 56–58). Inspired by these insights, robotic animals incorporate reward-based behaviours and playful interaction models, akin to those found in games. These mechanics encourage users to engage with the robots over time, fostering curiosity and attachment through iterative feedback loops.

1.4.10.2 Intelligent Toys as Experimental Platforms

Interactive toys like Anki Robotics (2016) *Cozmo* demonstrate the potential for fostering emotional engagement through adaptive behaviours and user-driven exploration. Giddings (2023) discusses how toys serve as experimental platforms, blending technology and imagination to produce compelling and relatable artifacts (pp. 102–104). In this research, robotic animals adopt similar principles, using expressive reactions and context-sensitive responses to evoke curiosity and deepen user relationships. The design builds on the idea that playfulness, as demonstrated by intelligent toys, enhances user interaction by prioritizing accessibility and emotional resonance.

1.4.10.3 Automata and the Tradition of Lifelike Machines

The historical study of automata, such as Vaucanson's *Digesting Duck*, provides critical insights into the design of lifelike behaviours in robotic systems. Giddings (2023) explores automata as both technological and cultural artifacts, highlighting their role in bridging the gap between functionality and lifelike mimicry (pp. 142–144). By incorporating subtle, lifelike movements—such as idle behaviours, simulated curiosity, or playful "errors"—modern robotic animals borrow from these early mechanical marvels to create systems that feel alive and responsive.

1.4.10.4 Unified Play-Centric Design

The interplay between games, toys, and automata forms a cohesive design philosophy for robotic animals. While games emphasize adaptive mechanics and long-term engagement, toys provide insights into playfulness and accessibility, and automata inspire lifelike mimicry and mechanical ingenuity. Together, these domains illustrate how play acts as a universal language, enabling robotic animals to resonate emotionally with users and serve as both functional tools and engaging companions.

Chapter 2 ANIMALNESS

In this chapter, I ask what makes something feel like an animal—not just look like one, but *feel* like one. Is it the tail? The way it blinks? The sound it makes when you drop your keys? I explore how shape, sound, texture, and movement contribute to the “animal feeling,” and why people believe a cardboard box with googly eyes might have feelings (sometimes).

I also try to draw a map of animality using toys, puppets, and robot ducks that poop (thanks, Vaucanson). It's a strange little zoo, but it helps.

This chapter doesn’t try to define “animal” in a strict way—it just tries to hold the idea gently and turn it around a few times to see what shines.

2.1 What is animal

An "animal" usually begins its definition in the realm of biology, where it’s boxed neatly into terms like "living organisms that eat organic matter, sense their surroundings, and respond to stimuli" (Merriam-Webster 2023). Or, if you’re feeling vague and minimalist, the Oxford English Dictionary’s take is "not a human or plant" (OED 2023). So far, so scientific—animals are bags of biology with nervous systems, metabolism, and occasionally some fur.

But as soon as you step out of the lab, the definition starts slipping through your fingers. Philosophers haven’t made it easier, either. Descartes thought of animals as instinct-driven machines (mechanistic materialism), while Schelling saw them as spiritual threads woven into the larger fabric of life (idealism). Somewhere in between these extremes lies the idea that animals aren’t just biological entities—they’re also emotional symbols, connecting the material world with human imagination.

And if science and philosophy weren’t complicated enough, society takes "animal" to another level entirely. Take the Dancing Lion, for instance. Here, performers donning fur-covered costumes don’t just move like lions—they mimic feline curiosity and emotional intensity, amplified by dramatic drumbeats that seem to echo the lion’s heartbeat. The careful choreography, combined with rhythm and physical gestures, transforms the performance into an emotional experience that makes the audience feel as though they’re face-to-face with something more than fabric and acrobatics: a living, breathing predator.

Figure 3 Dancing Lion performance by myself

Similarly, plush toys and puppets don't have bones or blood, yet they evoke the same affection as real animals. In games, characters like Pluto are unquestionably perceived as animals, even when their designs stray far from realism. On the other hand, Goofy, despite being from the same species, is much more human in his behaviors and interactions. As Finch (2015) notes, the distinction between Pluto and Goofy (Disney Characters) reflects how anthropomorphism interacts with societal perceptions of animality—where behavioral traits and social roles, rather than species, define whether something feels "human" or "animal."

But what makes the lion in the lion dance a lion and not just people jumping around in fur costumes? Why is Pluto undeniably a dog, while Goofy seems like a human in disguise? What specific features, gestures, or cues help these creations evoke the essence of an animal? As we move forward, these questions will guide a deeper exploration into the visual, auditory, tactile, and behavioral characteristics that define animality and help us blur the line between real and artificial.

Artificial life Continuous parallel Dichotomous Key containing BB-8	
1(10) Animal character appearance (mainly whether the head and face simulate animals)	
2(5) Physical presence(Visible and palpable in front of the person)	
3(4) Fur-covered	-----------PARO
4(3) No fur	----------Keepon
5(2) Without physical entity	
6(7) Helping and collaborating with humans	--------------Video Game *Zelda* "Giant Horse"
7(6) No obvious help or function for humans	
8(9) Network connection required (to transfer and share data)	-----------QQ Pet Penguin
9(8) Local data (no need to upload data or for Cloud Servers)	------------------Tamagotchi
10(1) Non-animal-like (meaning that the face or visual perception does not directly resemble that of an animal)	
11(14) Animal behavior (including animal-like emotions and cognition)	---------BB-8 Robot
14(11) of non-animal behavior (not of animal emotions and cognitive abilities)	
15(18) Human-like intelligence design (human-like way of communication and cognition)	
16(17) Unique identity (generally considered irreproducible, or with a special personality)	-----Sophia
17(16) Reproducible/no unique identity(without an exclusive name and identity)	------Siri
18(15) Non-human intelligence	
13(12) Movement and structure that are not 'animal-like	--------- Automatic floor sweepers
12(13) Acting in an animal-like body structure	-------Big Dog Robot

Figure 4 Dichotomous Key of verity of "Things"

At the beginning of my research, I created a dichotomous key as a tool to classify and understand the diverse entities that could be considered robot animals. Borrowing from biological taxonomy, this table provided a structured way to differentiate between virtual and physical beings, from PARO (a therapeutic robot seal with fur and tangible presence; Shibata 2012) to QQ Pet Penguin (a networked virtual pet that interacts digitally; Tencent 2025). The key used binary questions to explore traits like physical presence, animal-like behaviour, and technological dependency, encouraging an immersive reflection on what makes something feel like an "animal." For example, the comparison between BB-8 (a rolling robot from Star Wars with playful, animal-like movements; Disney 2015) and Big Dog (a quadrupedal robot with functional, mechanical movements; Raibert et al. 2008) forces us to think about how motion and design affect the perception of animality. Similarly, contrasting Tamagotchi (a virtual pet requiring care; Bandai 1997) with Keepon (a robot responding to social cues in real time; Kozima et al. 2009) highlights the different ways emotional connection can be evoked. By examining these categories, the table invites readers to reflect on the blurry, interwoven boundaries between animals, robots, and human imagination.

As the research evolved, it became clear that defining machine animals is not as straightforward as identifying a set of physical or behavioural traits. The contradictions in their classification reveal a deeper complexity. Some robots, like PARO, look and feel animal-like but lack certain behaviours we might associate with animals. Meanwhile, entities like Tamagotchi or QQ Pet Penguin have no physical presence or movement but create a strong sense of animality through their interaction patterns. Adding further complexity are cases like Goofy and Pluto—both anthropomorphic dogs, yet one is perceived as more human and the other as more animal (Finch 2015). These examples suggest that the perception of robot animals is not solely dictated by design. Instead, it emerges from an intricate relationship between their physical traits, behaviours, and how users emotionally and imaginatively engage with them. Robot animals are thus defined not just by their creators' intentions but also by the fantasies and personal connections formed by their users.

While the dichotomous key offered a helpful starting point for understanding robot animals, it also exposed limitations in this classification method. The biggest challenge lies in addressing cognitive abilities. As later research revealed, there are two main forms of cognition in robots: genuine cognition, where robots process real-time data through local systems (e.g., Keepon, which uses simple sensors to react autonomously), and perceived cognition, where behaviour is pre-set, remote-controlled, or network-driven. For example, robotic animals at Disney theme parks are designed to create the illusion of life through a combination of pre-programmed movements and real-time remote control by backstage operators. These robots (such as animatronic animals in *The Jungle Cruise* or *Pandora: The World of Avatar*) use carefully choreographed actions and interactive cues to make visitors feel as though they are encountering real, responsive creatures (Imagineering 2016; Broggie 2013).

This duality highlights that robot animals cannot be neatly categorised based on isolated features like appearance or behaviour. Instead, their animality can come from multiple overlapping sources—physical design, behavioural cues, and even the illusions they create. Perhaps these contradictions are not obstacles but opportunities. The blurry lines of robot animals definitions suggest that their "animalness" need not rely solely on biological imitation. It can also emerge from their ability to inspire emotional and imaginative connections, turning "fantasy" into a key component of their design.

2.2 look like animal

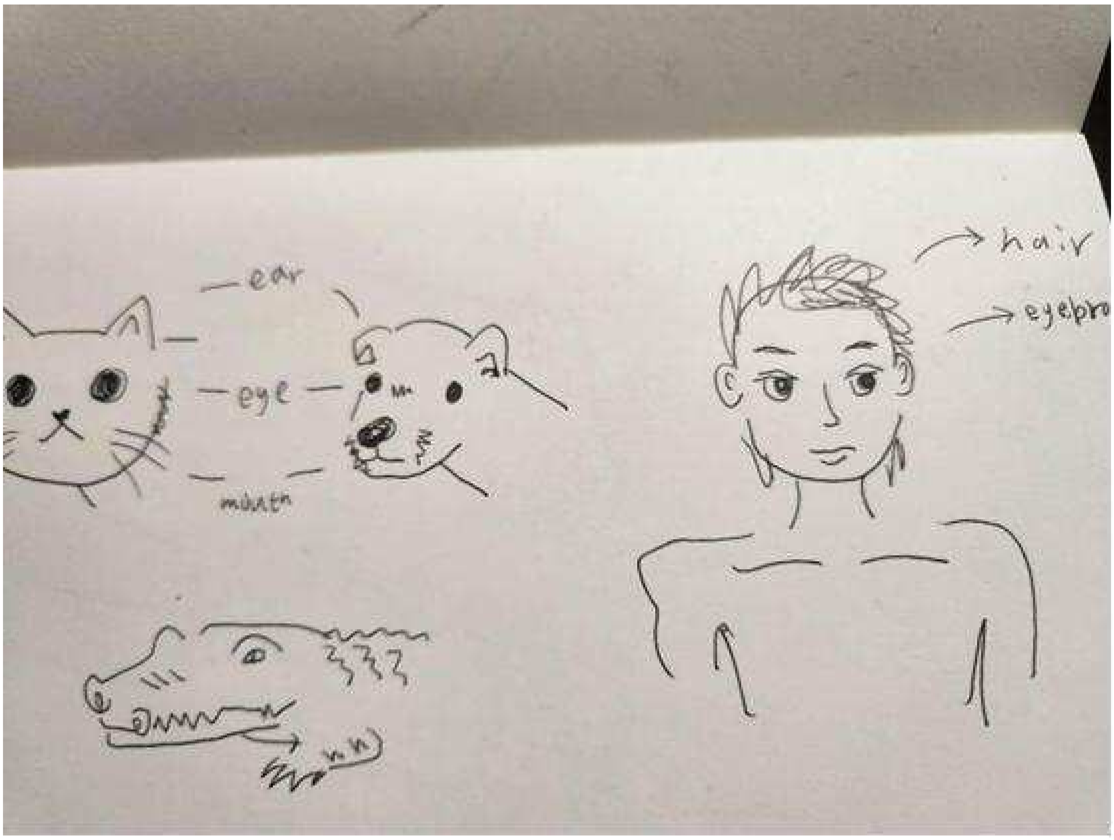

Figure 5 animal and human are different

Even in simple sketches, the differences between humans and animals are striking. Animals like cats, dogs, and crocodiles have long snouts and elongated, split mouths that follow the shape of their narrow skulls. Crocodiles and other predators often have exposed teeth, adding to their sharp, menacing appearance—features that are entirely absent in humans, whose mouths are small, subtle, and lack such pronounced skeletal extensions.

Eyes are another key distinction. Cats and dogs have large pupils with minimal sclera (the "whites" of the eyes), making their gaze appear more focused and unified, while humans' high-contrast sclera highlights gaze direction and adds expressiveness. Additionally, the eyes of animals like dogs and crocodiles are positioned on the sides of their heads, enhancing their peripheral vision, whereas human eyes are forward-facing and concentrated on a flat, rounded skull.

Animals also have prominent noses, often textured and coloured differently from their surrounding faces, with large, visible nostrils. Humans, in contrast, have smaller, smoother noses that blend into their overall facial structure. Furthermore, animals' faces are typically covered in fur or scales with unified textures and colours, while humans lack facial fur and instead feature eyebrows and hair (which uniquely grows indefinitely from the back of the head).

These features—elongated snouts, exposed teeth, whiskers, textured noses, and fur—make animals visually distinct from humans, even in the simplest representations. Such quick, intuitive differences lay the foundation for understanding how "animality" is perceived and replicated in robotic animals.

Charles Darwin, in *The Expression of the Emotions in Man and Animals* (Darwin 1872), analyzed the structural and functional differences in emotional expression between humans and animals. He noted that while animals are capable of facial expressions, their limited facial musculature and ecological needs make these expressions less central to communication. Instead, animals rely mostly on body movements and behaviours to convey emotions and intentions. We will discuss this further in the following chapters, where we explore how animals' actions and behaviours shape their interactions with the world and with one another.

Figure 6 crested gecko

The image above highlights the diverse visual characteristics of vertebrate eyes, providing a clear contrast between animals and humans. Features like the vertical pupils of geckos or the horizontally elongated pupils of goats immediately evoke a sense of "animality" that is distinct from the human experience. Reptiles, such as geckos, possess particularly unique and endearing traits—many species, like the crested gecko, have large, expressive eyes, soft and plump bodies, and even "eyelashes" (radiating dermal projections near their eyes, located around the nictitating membrane). These features add to their charm and appeal, showing that animality is not confined to mammals but can also emerge powerfully in reptiles.

2.2.1 Head Features: Ears, Eyes, and More

Ears: Prominent ears, whether upright like those of a fox or floppy like a spaniel's, are quintessential animal features.

Eyes: Distinctive eye shapes and orientations are key indicators of animality. Vertical pupils, as seen in cats and geckos.

Body Features: Fur, Shells, and Scales

Fur and Hair: A consistent texture of fur or hair across the body is a hallmark of many animals.

Shells: Protective shells, like those of turtles or snails, are distinctive features. While not commonly replicated in popular virtual characters, they remain strong symbols of certain animal classes.

Scales and Armour: Reptilian scales, as seen on crocodiles, or the armoured plates of pangolins, provide a rugged texture that is unmistakably animalistic. Toothless's design incorporates smooth, scale-like skin, enhancing his dragon persona.

2.2.2 Extremities and Appendages

Tails: Tails serve various functions and are prominent in animal anatomy. Characters like Meowth from *Pokémon* feature tails that add to their animal-like appearance (Tajiri 1996).

Claws and Pincers: Features like the claws of a crab or the talons of a bird are definitive animal traits. While not always present in virtual characters, such appendages can enhance the perception of animality.

Fins and Gills: Aquatic animals possess fins and gills, which are less commonly represented in mainstream virtual characters but remain iconic features of marine life.

Some Unusual Forms

Segmented Bodies: The jointed exoskeletons of insects or the elongated forms of snakes present unique silhouettes that are distinctly non-human.

Transparency: Creatures like jellyfish exhibit transparency, adding an ethereal quality to their appearance. This trait is less commonly adapted in virtual characters but offers a unique aesthetic.

The design of virtual and robotic characters often blends real animal traits with creative exaggerations, allowing them to bridge the gap between reality and imagination. Characters like BB-8 from *Star Wars* evoke animality not through anatomical resemblance but through behavioural cues such as head tilts, rolling movements, and expressive sounds that mimic small, curious creatures (Hidalgo 2017). Similarly, Toothless from *How to Train Your Dragon* builds on reptilian features like smooth, scale-like skin and large, rounded eyes, combining these with expressive ear-like appendages to create an endearing yet otherworldly creature.

Sonic the Hedgehog offers a different approach, taking the distinctive quills of a real hedgehog and merging them with human-like posture and dynamic motion to create a hybrid that feels both familiar and imaginative (Sega 1991). These examples illustrate how "animality" can be interpreted not only as a reflection of real-world animals but also as a platform for innovation, where designers can enhance, reimagine, or even defy natural boundaries.

The possibilities for artificial animal designs extend far beyond realism. By drawing on the rich diversity of real animal traits and layering them with creative liberties, designers can create forms that nature itself might never produce. A dolphin with fur, a dinosaur with wings, or even entirely new hybrids that blend the features of multiple species demonstrate how the visual and structural language of animality can be expanded into realms of pure imagination. These creations, rooted in the familiar yet stretching into the extraordinary, highlight the limitless potential of human creativity in shaping the concept of "animal" in both virtual and robotic forms.

2.3 Sound like animal

Animals rely on sound as one of their most versatile tools for communication and expression. From the deliberate calls of birds to the subtle rustling of fur or feathers, these auditory cues are deeply tied to their behaviour and identity (and often, to how humans emotionally connect with them). For robotic animals, capturing this auditory "animality" isn't just about imitating obvious noises like barking or chirping—it's also about recreating the incidental sounds that bring them to life, such as the rhythmic patter of feet or the faint vibrations of wings in flight. These small details ground the experience of the robot in reality, making it feel natural and authentic.

Animal communication is often perceived as simpler than human language, but this perception is more reflective of our limited understanding than of a true lack of depth. Unlike humans, who use structured grammar and discrete words to convey precise meanings, animals rely on holistic vocal signals—variations in pitch, loudness, and rhythm—to express emotions or immediate needs. Research by Suzuki et al. (2016) on Japanese great tits revealed that even bird calls can display syntax-like structures, where the order of sounds changes the message entirely. Similarly, Jane Goodall's observations of chimpanzees demonstrated the intricate role of vocalisations and gestures in their social interactions, ranging from warning others to bonding with group members (Goodall 1986). These findings highlight the richness of animal communication systems, which often go unnoticed simply because they don't align with human linguistic conventions.

This effort to connect is particularly evident in domestic animals, which have adapted their vocalisations to engage more effectively with humans. Cats, for instance, rarely meow to each other in natural settings but frequently use this sound to communicate with humans. Research by McComb et al. (2009) found that cats tailor their meows to capture human attention, combining high-pitched tones and rhythmic patterns that humans instinctively respond to. Similarly, Pongrácz et al. (2005) showed that humans are remarkably skilled at interpreting dog barks, such as distinguishing between playful, aggressive, or alarmed tones. These adaptations highlight how animals modify their communication to suit human auditory sensitivities, using sound not just to express themselves but to foster understanding in a cross-species context.

However, not all animal sounds are heard by human ears. Many creatures rely on ultrasonic or infrasonic frequencies to communicate or navigate their environments (like dolphins with echolocation or elephants with low-frequency rumbles). While this might seem like an exciting addition to robotic animal design, there's a practical and ethical concern: such sounds, though imperceptible to humans, could disturb real animals sharing the space (and could inadvertently stress household pets or even nearby wildlife). Therefore, including inaudible sounds in robotic animals requires not just a functional purpose but also careful thought about the unintended consequences. Designing robot soundscapes should prioritise what humans can perceive and emotionally engage with—creating immersive auditory experiences that are believable and respectful of both people and the creatures they share their environment with.

In Giddings' analysis of animal-like behaviour in video games, he (2020) discusses how the design of robotic and virtual creatures, such as the mechanical animals in *Horizon Zero Dawn*, effectively mimics real-world animal communication and behaviour. For example, auditory signals like howling, used by the game's robotic "Watchers" to alert their pack, mirror patterns found in natural animal communication. These carefully designed soundscapes serve not only to create a believable ecosystem within the game but also to evoke emotional engagement and immersion in the player. This approach demonstrates the importance of auditory cues in creating relatable and expressive virtual beings.

When considering how to design the sounds of robotic animals, the *Pokémon* series offers a compelling reference point. Characters like Pikachu express a wide range of emotions using variations of simple, species-specific vocalizations like "Pika-pika" or "Pikachu." These sounds are not complex in linguistic terms but rely heavily on tone, pitch, and rhythm to convey emotions such as happiness, anger, or confusion. Importantly, these vocalizations are not designed for the creatures to communicate with each other but to ensure that audiences—watching from outside the fictional world—can understand and connect with their emotions. This approach highlights a key principle for robotic animal sound design: the purpose is not merely to simulate communication but to enhance emotional engagement, making the sounds relatable and reinforcing the animality of the robot.

For robotic animals with no clear real-world counterpart, such as GUA or VECTOR, their sounds must strike a balance between originality and recognizability. These creatures can utilize a mix of synthetic and organic sound qualities, creating a unique "voice" that reflects their hybrid identity. For instance, the use of electronic tonalities—like modulated beeps or synthesized hums—can reinforce their mechanical essence while maintaining a sense of animal-like personality. At the same time, these sounds should align with their body movements to create cohesive and expressive behaviours. When a robotic animal tilts its head in confusion, for example, the accompanying sound should feature a questioning intonation, such as rising pitch, synchronized with the movement to produce a natural "head-tilt and vocal" effect. Similarly, when expressing frustration, the sound design might include sharp, rhythmic bursts that complement stomping or other emphatic physical gestures, amplifying the emotional impact of the behaviour.

To achieve this level of integration, sound design can incorporate several methods. One approach involves using pre-recorded animal vocal samples, synchronizing them with the robot's movements to match the rhythm and pacing of its actions. For example, chewing sounds can be paired with eating motions—even if the robot's mouth isn't producing mechanical friction—by layering organic chewing noises with subtle electronic effects. This blending can give the impression of a "real" interaction while maintaining the robot's unique identity.

For a more authentic and natural emotional range, human voice acting can also play a critical role. Voice actors can create a wide array of expressive sounds tailored to the robotic animal's personality and intended emotional repertoire. Post-production techniques, such as altering pitch, adding reverberation, or layering with animal sound samples, can then refine these recordings to remove overtly human characteristics while preserving their emotional depth. For example, a voice actor's playful giggle could be processed to sound like a chirp, or a growl could be blended with a low electronic hum to match the robot's identity. This method not only ensures greater flexibility in sound design but also provides a more cohesive and emotionally resonant experience for users.

However, the differences between human and animal vocalisation go beyond structure—they are also rooted in physiology and mutual misunderstanding. Humans rely on subtle vocal cord vibrations and fine motor control of the lips and tongue to create complex speech. In contrast, many animals generate sound using their entire bodies, with vocalisations often accompanied by physical gestures or movements (e.g., a wolf howling with its head raised or a horse neighing with its body tensed). These differences mean that both species struggle to fully interpret the other's intentions. As a result, communication relies on more universal cues, such as tone, rhythm, and volume. This is not because animal sounds lack meaning but because "language barriers" force both sides to focus on what can be mutually understood. For humans interacting with animals, it's similar to travelling in a foreign country where the spoken language is unfamiliar—instinctive communication through gestures and exaggerated intonation becomes the default.

In essence, the goal of sound design for robotic animals is to create vocalizations that feel intuitive and engaging while respecting the unique identity of the robot. Whether through synthetic sounds, animal-inspired samples, or post-processed human voices, the emphasis is on achieving synchrony between sound, movement, and emotional expression to evoke both relatability and wonder in the human user.

2.4 Feel like animal when touched

Touch, beyond being one of the most intimate senses, is essential in bridging the gap between robotic animals and their human users. It encompasses far more than just surface textures; it includes weight, volume, and the experience of hugging, squeezing, or interacting physically with the robot. Even the visual anticipation of texture—such as the spiky appearance of a hedgehog or the smooth sheen of a slug—contributes to the perception of animality. Factors like temperature, humidity, and material properties (whether metallic or organic, soft or rigid) further shape the tactile experience. These physical interactions create a sense of presence, turning robotic animals into tangible companions, distinct from flat, virtual entities.

The importance of touch also extends to how animals interact with their environment. Consider the common joke about cat owners: showcasing their pet isn't just about sharing photos but showing up covered in cat hair—tactile evidence of the animal's presence. This highlights how touch connects animals to the physical world and underpins their emotional resonance. For robotic animals, physicality is the pathway to transitioning from "fantasy" to "reality," making touch one of their most critical design elements.

PARO, the therapeutic seal robot, exemplifies how tactile design fosters emotional connections. Its soft fur and manageable size encourage users to hold it close, and research shows that hugging PARO can release oxytocin, offering comfort akin to interacting with a live animal (Shibata 2012). In contrast, robots like VECTOR and AIBO, despite their advanced interactivity, lack the tactile appeal to be hugged or cuddled. This limitation stems from their smaller size, harder materials, and mechanical design choices, which make them less relatable in physical interactions.

For a robotic animal to feel lifelike, it must balance various tactile factors. A sturdy body is crucial to endure physical interactions without feeling fragile. Weight adds a sense of substance—too light, and the robot feels insubstantial; too heavy, and it risks being cumbersome or unsafe. A fur-covered surface enhances tactile appeal but introduces challenges such as heat dissipation and durability. Many budget designs attach synthetic fur directly to hard plastic shells, which undermines the illusion of animality when touched. A more effective approach involves placing spongy or cotton-like material between the fur and the mechanical core to mimic the feel of muscle. However, this requires careful engineering to avoid issues like overheating or restricted movement in joints.

For the head and face, minimal padding is sufficient since real animals often lack substantial fat or muscle in these areas. This allows sensors—such as those for touch or temperature—to be placed closer to the surface for greater accuracy. This design choice not only enhances realism but also supports the functional needs of robotic systems.

Real animals offer valuable insights into tactile design. Fur, while reducing skin sensitivity, provides insulation and protection in harsh environments. Long-haired animals often rely on bones and muscles, rather than skin receptors, to sense physical interactions like rubbing or pressing. Robotic animals can replicate this through flexible materials and mechanical damping systems in joints, enabling them to detect forces such as pressure, shear, or impact. By interpreting these mechanical signals, robotic animals can respond to user interactions in a meaningful way. For example, they could distinguish between a light pat, a firm hug, or a playful push, translating physical feedback into emotional behaviours. Such systems bring robotic animals closer to biological realism, integrating bionic principles to create more adaptable and lifelike designs.

This tactile focus ensures that robotic animals are not only visually appealing but also physically engaging, offering users a unique and immersive connection. As robotic animals continue to evolve, touch-based design will remain central to bridging the gap between artificial creations and the rich, physical presence of living companions.

The tactile experience of interacting with animals is rooted in the unique physical properties of their bodies, which vary significantly across species. For example, the smooth and slippery texture found in amphibians, fish, or molluscs often results from a combination of reduced surface friction, the presence of mucus, or oily and watery secretions. A different type of smoothness, like the velvety texture of lotus leaves or the hydrophobic feathers of water birds, arises from microstructures on the surface. These tiny protrusions disperse surface tension, causing water and touch to glide effortlessly—similar to the scaled heads of reptiles, which often produce a smooth yet dry sensation.

Soft and squishy textures, such as those found in mammals or certain amphibians, reflect the presence of underlying muscle, fat, and elastic skin. These features provide animals with resilience and mobility while creating a tactile experience that feels lively and responsive. For instance, when hugging a dog or cat, the body’s firmness and pliability contribute to a comforting and realistic interaction—qualities that robotic animals must strive to emulate.

Warmth is another key tactile characteristic associated with animals, particularly endotherms. The heat radiating from their bodies comes from their ability to maintain a constant internal temperature, making their touch inherently inviting and lively. On the other hand, the cool, rigid feel of reptiles like snakes or lizards reflects their ectothermic nature and the structural arrangement of their scales. These scales, often arranged in orderly, overlapping patterns, create a textured, protective surface that adds to their distinctiveness.

Sharp textures, like the spines of hedgehogs or porcupines, serve as a tactile warning system. Similarly, coarse fur, rough skin, and rigid bristles, such as those on boars or crocodiles, create a sensation of durability and strength. The wrinkled and keratinised folds on a crocodile's skin, paired with its tough, armour-like texture, convey a sense of ancient, rugged power. In contrast, the fine, sparse hair found on some animals—like elephants or newborn rodents—feels delicate and transient, evoking a sense of fragility.

The tactile experience also extends to moisture. Materials that retain water, such as the damp surface of a dog's nose or the sticky grip of a frog's feet, create a cool and slightly adhesive sensation. Such textures, while unusual, are deeply tied to the animal's biology and are a testament to the diverse physical properties of living beings.

The fascination with animal textures is well-documented among enthusiasts, who often describe their tactile interactions in vivid detail. For example, reptile keepers commonly highlight the leathery yet smooth texture of snake scales, while bird owners appreciate the soft but firm resilience of feathered wings. Online forums, such as reptile care communities or pet owner blogs, frequently discuss the sensory joys of interacting with animals, providing a wealth of descriptive feedback.

Books like *Why We Love Dogs, Eat Pigs, and Wear Cows* by Melanie Joy (2010) explore the emotional and sensory connections humans have with animals, emphasising the role of touch in fostering these bonds. Moreover, studies of human-animal interactions indicate that tactile contact—whether stroking, hugging, or simply holding an animal—creates a profound sense of connection and empathy. For robotic animal designers, these insights highlight the importance of capturing not only the tactile properties of animals but also the emotional resonance that these textures evoke.

By incorporating feedback from both animal enthusiasts and scientific research, robotic animal design can achieve a more nuanced understanding of tactile appeal. From the cool, wet sensation of a dog's nose to the soft resilience of a mammal's fur-covered body, each element contributes to a more realistic and immersive interaction, turning the robotic animal into a believable and emotionally engaging companion.

Achieving realistic and emotionally resonant robotic animals relies not only on the development of advanced biomimetic materials but also on the integration of traditional artistic disciplines such as puppet-making and sculpture. These two fields—modern material science and time-tested artistic techniques—provide complementary insights. The former offers access to innovative, life-like substances, while the latter contributes a deep understanding of how textures, shapes, and forms can evoke vitality and believability. Together, they enable the creation of robotic animals that feel nuanced and alive.

The tactile characteristics discussed earlier come from the immense variety of textures and materials found across species. While the goal is not to replicate every animal in existence, mastering the production techniques for a range of materials is essential to crafting highly detailed and expressive designs. A single animal, such as a horse, already demonstrates how diverse materials must be combined seamlessly to mimic its various physical traits:

- Hard, resilient hooves require a combination of metals and high-strength organic polymers to replicate their durability.
- Short, dense fur covering the body can be imitated with synthetic fibres designed to mimic the tactile sensation of animal hair.
- Long, flexible mane and tail hairs demand materials that are not only soft but also resilient to friction and motion, such as modified silicone or nylon.
- Soft, pliable noses require a mixture of silicone and glycerine to emulate the elasticity and slight moisture found in real animal skin.
- Moist, expressive eyes can be crafted with hydrophobic polymers to mimic tear film while ensuring clarity and durability.
- Calcified teeth and flexible tongues might involve calcium-based materials for the former and food-grade silicone for the latter to achieve the right balance of hardness and pliability.

This level of detail is impossible to achieve by relying on only one or two types of material. Using limited materials would produce, at best, an appliance-like robot (more akin to a washing machine) or a simple plush toy—neither of which captures the intricate, multi-sensory experience of interacting with a living creature.

By diversifying materials and combining their unique properties, designers can create robots that exhibit a compelling level of realism and sophistication. The synthesis of cutting-edge polymer research with the craftsmanship of traditional art forms provides the foundation for robotic animals that are not only functional but also emotionally engaging. Such designs are capable of elevating robotic animals beyond mere machines, transforming them into companions that embody both scientific innovation and artistic mastery.

2.5 Move like animal

The observable behaviour of animals is a fusion of body movements and sounds, creating a distinct expression of their intent, emotion, and interaction with the world. Movement is perhaps the most direct form of communication, whether it is a daily action like walking or a social behaviour like bowing to signal playfulness. In this section, movements are divided into two primary categories: daily maintenance actions and social actions. These classifications, while not exhaustive, serve as a foundation for understanding animal behaviour and inform the design of robotic animals that aim to replicate these natural patterns.

The observable behaviour of animals, blending body movements and sounds, provides critical insight into their interaction with the environment, their emotional states, and their social dynamics. Traditionally, animal behaviours are categorised into two primary groups:

- **Daily maintenance actions**: These include feeding, grooming, resting, and other activities essential for survival. For example, the rhythmic pecking of birds, the grooming rituals of cats, or the slow basking of reptiles. Such actions, though mundane, are critical indicators of health and vitality.
- **Social actions**: These include play, aggression, mating rituals, and cooperative behaviours. A wolf bowing to initiate play, a horse flicking its tail in agitation, or a chimpanzee offering grooming to build alliances all reflect the social depth of animal behaviour.

Nikolaas Tinbergen (1963) argued that studying these behaviours provides insight into the adaptive significance of animal actions, forming the backbone of ethology. By categorising animal behaviour into functional groups, researchers can better understand not only survival mechanisms but also the social and emotional dynamics that underpin animal societies.

For robotic animals, replicating these categories of movement is not merely about mechanical mimicry but about capturing the *meaning* behind the motions. For example, the wagging of a robotic dog's tail must not only simulate the motion of tail-wagging but also convey the emotional undertones—whether excitement, nervousness, or appeasement. Similarly, the simple act of a robot "resting" could signal calmness, recharge, or even simulated sleep, inviting users to interpret the behaviour as more than mechanical downtime.

Kleiman (1986) noted that the study of behaviour requires both detailed observation and contextual interpretation, as behaviours often carry layered meanings depending on environment and social context. For robotic systems, this means movement design must consider not only biomechanics but also timing, rhythm, and situational cues. A twitch, a pause, or even a stumble can be imbued with narrative weight, creating opportunities for emotional connection.

In practical applications, robotic animals can use simplified behaviour models that emphasise recognisability over complexity. For instance, a robotic cat might knead its paws against a surface to signal comfort, or a robotic bird might preen its wings as a way to display self-maintenance. These simplified cues tap into human familiarity with animal behaviour, allowing users to project emotional meaning onto the actions.

At the same time, robotic animals can extend beyond biological realism. Inspired by Wilson's (1975) sociobiology, designers might introduce exaggerated or hybrid behaviours to emphasise particular qualities—such as a robotic dragon that arches dramatically to display dominance, or a mechanical fish that performs looping dances to express play. These "extra-natural" behaviours, while not biologically accurate, can still feel animal-like if they draw from the rhythm and intent of real behaviours.

Ultimately, movement is a language. By carefully designing robotic animals to "move like animals," researchers and designers can create companions that are not only believable but also emotionally resonant, bridging the gap between machine and life through the universal grammar of motion.

Maintenance behaviours and social behaviours. This distinction not only reflects ethological classifications but also serves as a foundation for designing robotic animals that aim to replicate the complexity of real animal actions (Tinbergen, 1963).

2.5.1 Two Categories of Behaviour

Maintenance Behaviours: These are non-social behaviours that sustain the animal's physiological and survival needs, such as eating, drinking, resting, and self-grooming. They often follow predictable patterns and include responses to environmental stimuli—for example, a cat grooming itself to cool down in hot weather, or a turtle retreating into its shell when startled. The relationship between an animal's structure and its motor skills plays a significant role in shaping these behaviours (Kleiman, 1986).

Social Behaviours: These are interactions between individuals, either within or across species. They can be further divided into categories such as affiliative behaviours (e.g., grooming or nuzzling to strengthen bonds), aggressive behaviours (e.g., displays of dominance or territorial defence), and reproductive behaviours (e.g., courtship displays or parental care). Social actions often combine physical movements and sensory signals—sound, scent, or colour changes—to communicate intent or emotion (Wilson, 1975).

2.5.2 A Three-Dimensional Framework for Robot animal Behaviour

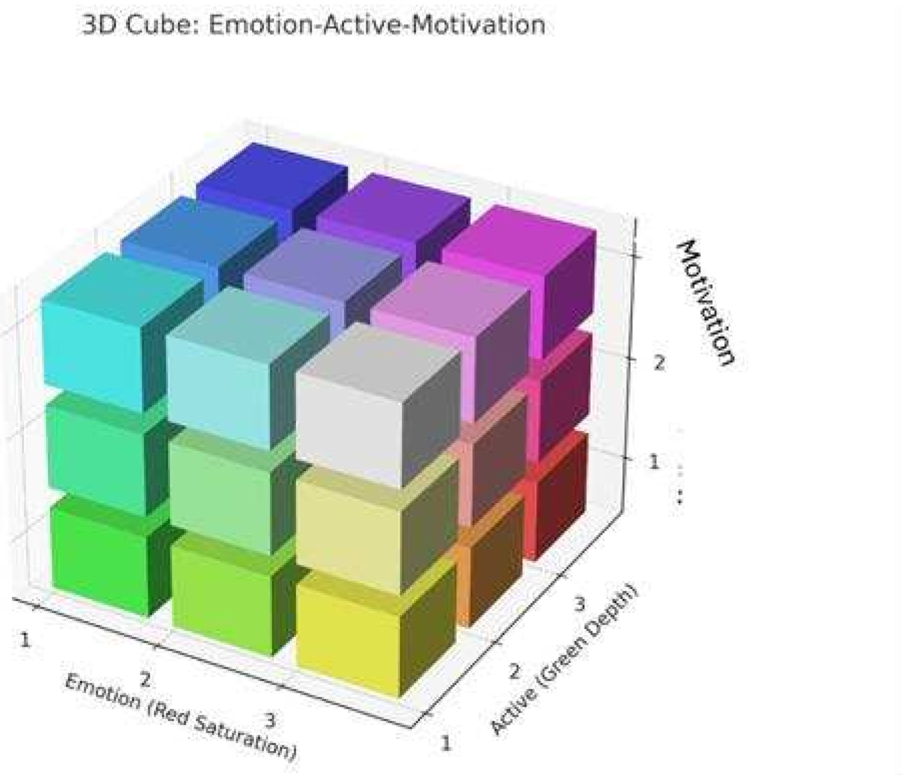

Figure 7 3D Cube: Emotion- Active- Motivation

While these two categories provide a solid starting point for analysing animal actions, they are insufficient for robotic animal design, which must translate natural behaviour into programmable frameworks. To address this, I propose a three-dimensional model that includes emotion, activity, and motivation as independent but interrelated factors. These dimensions allow for a more flexible and nuanced behavioural design:

Emotion: Represents the internal state of the robot, such as calmness, fear, or excitement. This affects how behaviours are expressed (e.g., a slow, relaxed walk versus a hurried, fearful pace).

Activity: Captures the level of energy or movement, ranging from passive states like resting to active states like exploring or running.

Motivation: Explains the purpose of a behaviour, whether it is driven by social interaction (e.g., seeking attention), environmental exploration (e.g., navigating a room), or survival-like needs (e.g., simulated feeding).

This approach acknowledges that real animals combine these elements dynamically. For example, a dog might exhibit high activity with low social motivation (stereotypic pacing) or low activity with strong social motivation (resting near its owner).

Animal behaviours often resist strict categorisation. A bird preening may appear to be purely maintenance-oriented, but it can also function as a signal of trust during courtship (an affiliative behaviour). Similarly, a cat's purring might accompany maintenance behaviours like resting, while also serving as a form of communication to express contentment or request attention. These overlaps highlight the complexity of animal actions, which robotic systems must simplify without losing believability.

Robotic animals designed with this framework can simulate both maintenance behaviours (e.g., "eating," "sleeping") and social interactions, avoiding the impression of being mere "social robots." Instead, they present themselves as entities with multi-faceted lives, capable of independent actions and responses, even in the absence of human input.

2.5.3 Human–Animal Relationships and Robotic Design

Beyond the physiological and behavioural aspects of animals, the relationship between humans and animals plays a pivotal role in designing robotic animals that can convincingly mimic the bond shared with real companions. This aspect leans heavily toward the user experience, focusing on how to evoke emotional connections and foster meaningful interactions.

This involves designing robots capable of long-term engagement, akin to nurturing relationships with live animals. Elements such as guided interactions, character backstories, and interaction-based rewards—common in game design—can amplify the user's imagination and strengthen the perceived relationship with the robotic animal. These strategies will be explored further in the following sections, where I discuss specific design implementations and their broader implications.

2.5.4 Aggression Behaviours

In my initial understanding, animal aggression can be broadly characterised by behaviours such as biting, striking, pushing, pouncing, and clawing—actions inherently associated with the potential to cause harm. However, aggression in animals is not limited to expressions of anger or defensive responses to threats. Instead, it encompasses a wider spectrum of behaviours with diverse functions, including hunting, play, competition, and challenges for resources or hierarchy.

Crucially, these behaviours are not always rooted in negative emotions. For predators, aggression can be instrumental, a natural component of securing food through hunting. In social animals, physical play often mimics aggressive actions—such as pouncing or mock-biting—yet serves primarily as a means of learning motor skills, testing boundaries, and strengthening social bonds. Similarly, within hierarchical groups, displays of aggression function as ritualised signals, establishing dominance or negotiating access to resources without necessarily escalating into severe conflict.

This broader perspective shows that aggression is better understood as a multi-purpose behavioural strategy, rather than a simple manifestation of hostility. For robotic animal design, this raises key questions: should aggression be entirely excluded to preserve the robot's role as a safe and friendly companion, or should simulated forms of aggression—ritualised, playful, or symbolic—be integrated to reflect the complexity of real animal interactions? Including such behaviours, even in attenuated or stylised forms, could enrich the believability of robotic animals by acknowledging that animal life is not defined solely by harmony, but also by competition, testing, and negotiation.

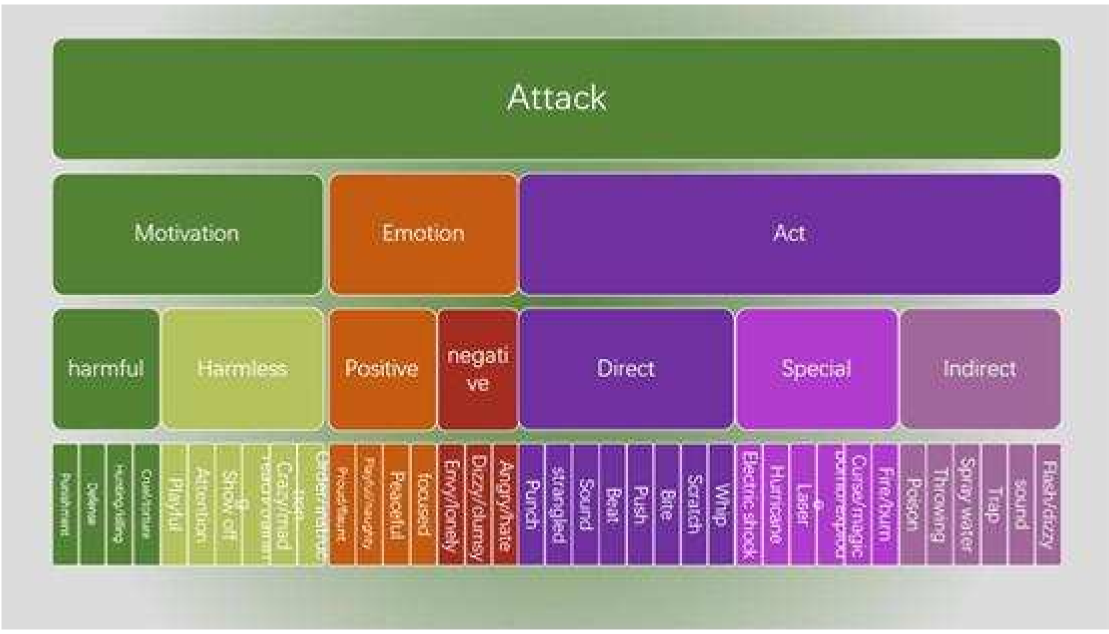

Figure 8 Different Attacks

Aggressive behaviours aren't always about brute force. Sometimes, they're about bluffing, playing, proving a point, or even just being a little annoying. Different animals have different ways of being "aggressive" (or at least appearing so), and the motivations behind these behaviours are often more interesting than the actions themselves.

Crocodiles aren't exactly social butterflies, but they do have a way of settling disputes without full-on fights (which makes sense when both sides have an equal chance of getting seriously injured). When faced with a larger, potentially dominant crocodile, a smaller one might respond with defensive aggression—freezing up, hissing, or even performing an exaggerated, slow retreat to avoid conflict while still looking "tough" (Dinets, 2015). It's intimidation theatre, but it works.

Young tigers don't just lounge around looking majestic from day one—they play-fight constantly, pouncing on their siblings, biting (but not too hard), and wrestling. These playful attacks help them develop motor skills and social awareness, but the key is that they're not actually trying to hurt each other. This is aggression in the same way that a game of tag is "chasing." Fun, necessary, and occasionally resulting in a little too much enthusiasm (McCune, 1995).

Some male birds don't bother fighting physically at all—they weaponise their voices instead. Species like nightingales engage in "song duels," where they interrupt, outmatch, and override each other's singing in an attempt to outshine a competitor. This is essentially musical smack talk, and the most persistent and complex singers are often the ones that win mates (Catchpole & Slater, 2008). So yes, sometimes being the loudest in the room does work—if you're a bird.

If you've ever had a cat, you've probably been ambushed at least once. Cats—especially younger ones—love to stalk, hide, and launch surprise "attacks" on their owners, often from behind furniture. It's a mix of play, practice, and the feline equivalent of saying, "Hey, pay attention to me!" Interestingly, cats don't really "meow" at each other much in the wild, but they do develop special vocalisations just to communicate with humans (Bradshaw, 2013). So, in a way, they've adapted their aggression and their communication skills just for us

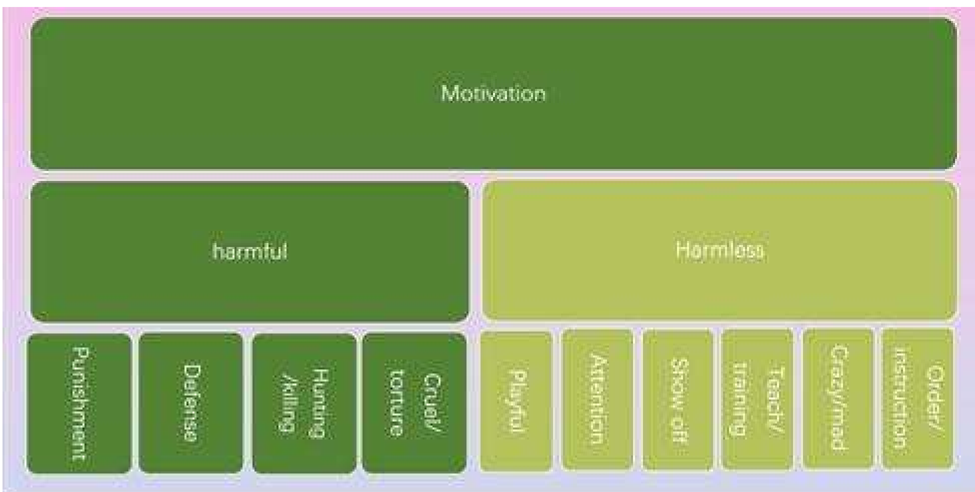

Figure 9 Different Motivation for aggressive

In the diagram above, aggressive behaviour is divided into two categories: those with harmful intent and those without. When people think of "aggression," they often associate it with deliberate harm and negative emotions—biting, scratching, or attacking out of anger. But in reality, aggression is far more complex. Play-fighting between tiger cubs, a dog excitedly knocking over its owner, or two cats engaging in dramatic (but harmless) wrestling—all of these fall under aggressive behaviour, yet their intent is entirely different from that of a truly hostile attack.

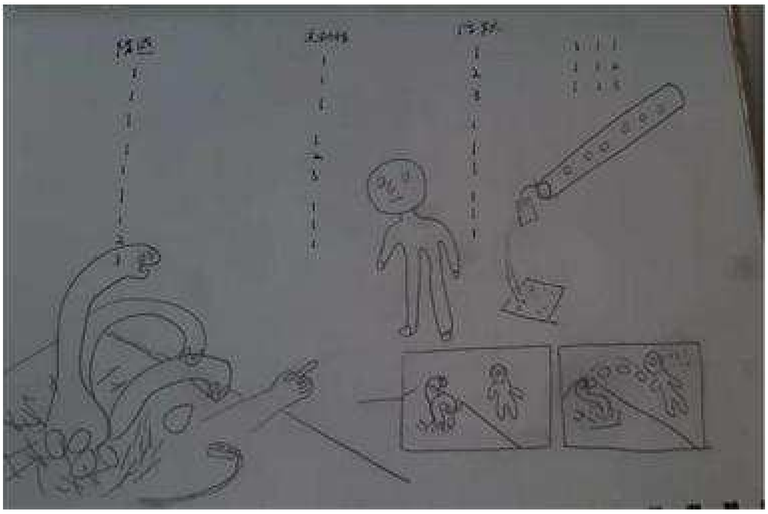

Figure 10 Attack behaviour

Through my experience with animals, I've realised that aggression isn't always about conflict—it's deeply tied to relationships, emotional bonds, and social structure. Particularly in cases of non-harmful aggression, these behaviours often emerge in intimate relationships. Animals that are uncomfortable or indifferent to a human will generally remain neutral—cautious or passive in their movements. But when an animal truly trusts and cares about someone, it may engage in non-harmful aggressive play (pouncing, mock-biting, or pushing).

On the other hand, harmful aggression tends to be rooted in self-defence, frustration, resource guarding, or the protection of a loved one. I've personally experienced this with my own dog, who once growled and snapped (without actually biting) at my ex-boyfriend—not because the dog was simply aggressive, but because he felt protective of me. In such cases, aggression is not an expression of cruelty, but rather a clear and controlled expression of emotion (though, of course, it can still create social complications—especially if the aggression is directed at someone you'd rather not offend).

When designing robotic animals, outright harmful aggression should be avoided (for obvious reasons). However, the intent behind aggressive behaviour can still be meaningfully expressed through carefully designed non-contact displays of hostility or defence. For example, consider a robotic animal's defensive reaction when it perceives a threat. A real animal in this situation might instinctively lunge or bite, but a robotic version can be programmed to use a combination of sound, posture, and movement instead—such as a sharp, sampled growl (processed from real animal sounds), a sudden forward jerk of the head, or a raised limb that simulates an incoming strike but never follows through. These controlled gestures create an effective illusion of aggression without the risk of actual harm.

For larger, sturdier robotic animals, their defensive behaviour should be even more restrained. Imagine a "calm monk-like bear," a "not-hungry dinosaur," or a "thick-skinned herbivore"—these robots wouldn't need to flinch or panic at threats; instead, their defence would be subtle but firm. A massive robotic quadruped, for instance, might swing a forelimb in a slow, deliberate motion, not to strike, but to create personal space. Alternatively, it could turn its body sideways as a physical barrier, glance over its shoulder in mild irritation, or exhale audibly to express dissatisfaction. These gestures signal rejection without aggression, reinforcing a feeling of controlled dominance rather than reactive hostility.

2.5.5 Learning from Animal-Friendly Spaces

We might take inspiration from petting zoos and child-friendly animal enclosures, which are designed to allow safe interaction while minimising actual aggressive encounters. At such facilities, large animals like horses or alpacas are often kept behind low fences, allowing humans to interact with their heads and necks while ensuring that their more dangerous limbs (like kicking legs) remain out of reach.

Interestingly, these enclosures do not completely eliminate mild aggressive interactions—a horse may still nip, and an alpaca might spit—but these behaviours, while technically aggressive, are seen as acceptable (and even educational) in helping humans better understand different species' temperaments. Similarly, robotic animals should be designed to express non-harmful aggression, allowing for a realistic but safe interactive experience.

In my ongoing (and sometimes stubborn) discussions with Dr. Anne McBride, she was quick to point out that my initial definition of aggression was far too broad (which, admittedly, I had suspected but wasn't quite ready to concede). While I originally considered any forceful, confrontational action—biting, pouncing, or striking—to be aggressive, she insisted that true aggression, in ethological terms, is directly tied to negative emotional states, such as fear, frustration, or defensive intent. Actions like predation or rough play, despite looking aggressive, don't fit this definition because they are not driven by hostility. A lion hunting a gazelle isn't "angry"; it's focused, calculated, and likely excited at the prospect of a meal. Similarly, young animals play-fight not to harm but to develop motor skills, social bonds, and even stress-coping mechanisms.

In Small Prey Species' Behaviour and Welfare: Implications for Veterinary Professionals, McBride (2017) explains that aggression is fundamentally about conflict—whether between individuals of the same species or in response to external threats. Predatory behaviour, by contrast, is a goal-driven activity tied to survival, and playful mock-battles between juveniles serve as developmental exercises rather than expressions of hostility. This distinction is essential, especially when designing robotic animals that mimic natural behaviours. If aggression is tied to emotional states rather than just physical force, then a machine programmed to "bite" isn't truly displaying aggression—it's merely executing a movement pattern. For robotic animals to convincingly simulate aggression (or any complex behaviour), they must either possess or convincingly emulate the internal emotional states that dictate these actions—something I'll return to in later sections.

Because robotic animals—especially hybrid-species fantasy creatures—must display aggression in a way that aligns with human expectations rather than real animal cognition, their "aggressive behaviors" inevitably become stereotyped or simplified representations of aggression. Due to the wide variation in aggressive behaviors across different animal species, I recognize that my definition of aggression in robotic animals differs from how real animals process and exhibit aggression. However, I still insist on using my "pan-aggression" concept to classify behaviors in robotic animals.

This structured classification serves a dual purpose: first, it allows robotic animals to process different stimuli and determine when to exhibit aggression, ensuring that their responses are predictable and understandable to human users. Second, it helps guide human interaction, making aggressive behaviors not just an expression of hostility, but also a communicative tool. When a robotic animal displays aggression, it can function as "negative feedback," signaling to the user that something in their interaction needs to change. This creates a learning loop where the human must adjust their behavior to build trust and improve their relationship with the robotic animal—much like how real animals and humans gradually establish mutual understanding through repeated interactions.

A note on "aliveness" and "autonomy"

In this thesis, I use the words "aliveness" and "autonomy" a lot—not as technical terms, but as ways to describe different kinds of presence.

Aliveness, here, is not about how realistic a machine looks, or whether it copies an animal well. It's about whether it feels like a being with its own rhythm. Not something made only to perform for humans, but something that seems to live with the environment—doing things for itself, or simply responding in ways that aren't always about us. That's what animals do: they don't act just for people. Sometimes they rest, avoid, twitch, wander, or do nothing. This kind of wholeness is part of what makes a being feel alive.

Autonomy, on the other hand, is more about systems. It's the difference between a puppet and a creature. Some robots are physically impressive but controlled like puppets—either by people or by cloud-based agents like ChatGPT. That's not autonomy. That's just moving the strings offstage.

A real fly has more autonomy than many robots with twenty degrees of freedom. Because autonomy isn't about complexity. It's about whether the thing acts on its own, even a little, even if badly.

This project tries to give machines a bit of that: not just scripted responses, but behaviour that emerges from what the robot senses, what it "feels like" doing, and how the world around it changes.

Chapter 3 Robot Animal Design

Now that we have an idea of what "animal" might mean, this chapter turns to how to build one—from motors to microcontrollers, from fur to feelings. It is technical, yes, but not cold. The focus here is on safety (no exploding limbs), soft materials (squishy is good), and how different parts of the robot have to "listen" to each other.

There is also a section on lifespan and breakdowns, because even robot animals can get tired or misunderstood (especially when chewed). This chapter marks the point where fantasy begins turning into circuits.

3.1 Move Ability Structure

The structure of a robotic animal directly determines how it moves, how flexible it is, and what kind of physical limitations it faces. Unlike industrial robots designed for precision and efficiency, robotic animals need to balance mechanical feasibility with natural-looking motion. If a robot moves too rigidly, it loses its "animality," but if it is too flexible or biologically accurate, it risks becoming fragile, inefficient, or overly complex to control. Many existing designs take inspiration from real animals, adapting their movement styles to match different functional goals. For instance, Boston Dynamics' BigDog follows a quadrupedal walking model, mimicking the leg mechanics of large mammals to maintain stability across uneven terrain (Raibert et al., 2008). In contrast, EPFL's Salamander Robot relies on a flexible spine to transition between crawling and swimming, demonstrating the advantages of reptilian and amphibian motion (Crespi et al., 2005). Some designs, like Festo's Bionic Kangaroo, take a more unconventional approach by focusing on energy-efficient jumping rather than traditional walking, incorporating a tail to store and release kinetic energy efficiently (Haldane et al., 2016). These different structural choices show how robotic animals must prioritise specific movement goals, whether it is agility, stability, or efficiency.

Beyond quadrupedal and bipedal robots, more experimental designs challenge the standard mammalian framework. Multi-legged robots, such as those inspired by spiders and octopuses, utilise additional limbs for enhanced stability and omnidirectional movement, making them particularly useful for complex terrain exploration (Menon et al., 2018). Soft-bodied robots, often modelled after cephalopods, use deformable structures to achieve fluid, organic motion, especially in underwater environments (Laschi et al., 2012). Even within the same movement category, the number of joints and degrees of freedom (DOF) dramatically affect a robot's realism and adaptability. A simple four-legged machine with stiff limbs may only be capable of marching in a straight line, while a multi-jointed quadruped can crouch, leap, and even mimic more expressive, animal-like postures. This underscores the importance of structure as a design constraint—a robotic animal must not only appear natural but also be engineered for reliability, repeatability, and user interaction. These considerations will be essential in later discussions on how movement shapes user perception and how mechanical limitations influence design decisions in the GUA project

3.2 Interaction Ability Structure

The social structure of robotic animals—their ability to interact, express emotions, and communicate through behaviour—is inseparable from their movement capabilities. A robotic animal's physical design not only defines its mobility but also dictates how convincingly it can express itself. Through continuous refinement in my research, I have realised that a concise and controllable structure for mimicking animal expressiveness requires two key design elements: large-scale spinal and locomotion-driven movement for broad emotional expression, and small-scale facial and appendage movement (mouth, tail, ears, wings, fins) for fine-tuned, detailed communication.

The spine is the core of expressiveness—not just because most animals that humans bond with are vertebrates, but because spinal-driven motion is the single most evocative movement pattern that signals "life". This is not just about gross motor functions; many of the most socially expressive behaviours in animals are fundamentally spinal actions. Head tilts, body arches, tail flicks, full-body undulations—these are all spinally controlled gestures that contribute massively to how an animal communicates. A robotic animal's spinal design isn't just about locomotion—it's about emotional nuance.

However, spinal motion alone is not enough—locomotion plays a fundamental role in perceived social capability. Nearly all animals that humans consider socially engaging have the ability to move freely. Animals that lack voluntary locomotion, such as barnacles, sea anemones, or certain mollusks, are generally perceived as passive or lower-order creatures, regardless of how complex their behaviour might actually be. The inability to move can fundamentally limit how people interpret an entity's intentions and interactions—a robotic animal that remains static risks being perceived as a decorative object rather than a social companion.

This is particularly evident in snakes, which are frequently mischaracterised as antisocial due to their lack of limbs and overt facial expressions. In reality, snake communication relies heavily on precise, deliberate spinal movements—from the way they coil and posture to signal aggression or trust, to the way they rhythmically sway during courtship. Some species, like garter snakes, even engage in complex group dynamics, forming massive mating aggregations where their spinal movement patterns serve as direct social cues (Shine et al., 2003). The argument that "vertebrate-based motion aids social recognition" is therefore not limited to mammals—it extends even to reptiles, whose expressiveness is encoded in their entire body posture.

This principle extends beyond terrestrial animals. Water-dwelling creatures also rely on fluid, spine-driven motion to communicate and interact. Robotic fish, such as those developed by MIT's Soft Robotics Lab, use segmented, flexible bodies to mimic the wave-like motion of real fish. This not only enhances their ability to move efficiently in water but also enables more organic, emotionally expressive movements, such as hesitation before a turn (suggesting curiosity) or sudden acceleration (indicating alarm). Research on bio-inspired robotic fish suggests that such fluidic body motion makes robotic creatures feel significantly more "alive" to human observers (Katzschmann et al., 2018).

While large-scale motion contributes to overall expressiveness, finer movements—especially in wings, fins, and antennae-like structures—play a crucial role in conveying emotion and state of mind.

Take butterflies, for instance. Their delicate, asynchronous wing beats can subtly indicate excitement, alertness, or even relaxation. A butterfly with rapid, erratic flutters conveys agitation or distress, while slow, rhythmic wing movements suggest calmness. This principle has been successfully replicated in robotic butterflies, such as Festo's Bionic Butterfly, which achieves a remarkable illusion of life by adjusting wing stiffness and flutter frequency (Festo, 2018). Similarly, robotic dragonflies use their independently controlled wings to replicate hovering and darting motions, making them appear more alert and reactive.

Fins operate under the same principle. In marine animals, fin movement isn't just about propulsion—it's a direct reflection of their internal state. A stingray's undulating pectoral fins, for example, change frequency depending on its stress levels or interaction intent. Robotic manta rays, like those designed by Harvard's Biodesign Lab, use soft, deformable materials to replicate these subtle state-dependent shifts in movement, which help them communicate not through sound or direct physical gestures, but through motion alone (Cianchetti et al., 2014).

For finer details—eyes, tails, and ears—generic mechanical solutions are often insufficient. Instead, dedicated biomimetic designs must be developed. For example, the diagram below illustrates an artificial eye mechanism in which two interlocking ring segments control the movement of an eyelid, simulating the contraction and expansion of a sphincter muscle. Unlike conventional gear-driven rotation, this design uniquely balances mechanical simplicity and naturalistic motion, demonstrating the necessity of customised mechanical solutions in robotic animal design.

Figure 11 Baobao Wang robot dog without fur cover

When designing robotic animals, it's tempting to focus only on big movements—spinal flexibility, locomotion, balance. But small details matter too. The way an ear flicks, a tail curls, or a paw grips can make or break the illusion of life. Some robotic designs prioritise functional bio-mimicry (helping robots move better, grip, or interact with surfaces), while others focus on expressive bio-mimicry (making robots more interactive and communicative). The most convincing robotic animals will likely need both.

Take Li Wen's remora-inspired suction disc. His team developed a robotic suction system mimicking the natural striped microstructures found in remora fish, allowing for adaptive grip, where each section of the disc adjusts independently (Wen et al., 2015). This means it's not just sticking to a surface—it's dynamically gripping, just like a real remora would on a shark. While originally designed for underwater applications, this concept could be repurposed in robotic animals—imagine a robotic lizard that grips onto surfaces like a real gecko, or a robotic octopus that gently attaches itself to human skin in a natural way.

Then there's Dai Zhentong and his team's research on gecko-inspired adhesion. By replicating the microscopic setae structures on gecko feet, his work enabled robots to cling to vertical and even inverted surfaces without using suction or glue (Dai et al., 2002). This is primarily a locomotion breakthrough, but it also raises interesting possibilities for social expression. Imagine a robotic gecko using this ability to cling onto a user's arm, mimicking real-life behaviours that signal trust and curiosity.

Meanwhile, the Umamimi robotic horse ear takes a completely different approach. Instead of replicating movement efficiency, it focuses on communication. Horse ears are incredibly expressive, shifting subtly to show interest, irritation, or alertness. The Umamimi system faithfully reproduces this, using motorised ears that react naturally to stimuli (Umamimi, 2019).

Even without sound or complex facial expressions, a robotic horse—or any robotic animal using a similar mechanism—could signal emotions in a way that feels instantly recognisable to users.

Figure 12 Umamimi horse ear

The development of robotic animals is a process of continuous refinement, balancing expressiveness, control, and practicality. My structural design evolved through several key iterations, each addressing different challenges in movement, interaction, and stability. I began with a 6-degree-of-freedom (DOF) linear structure, allowing for basic spinal movement. While flexible, it lacked expressiveness. Adding an articulated mouth improved behavioral cues, but full-body movement remained limited. I then tested four-legged locomotion with blinking eyes, aiming for a more lifelike presence, but the complexity of gait control and power constraints made it impractical.

To balance realism and control, I transitioned to a Mecanum-wheel platform with a 6-DOF robotic arm and an articulated mouth. This allowed for omnidirectional movement (via wheels) without complex leg algorithms, and expressive gestures (through the robotic arm) mimicking head tilts or ear flicks. A functional mouth, enhancing communication.

Each iteration refined the trade-offs between realism and feasibility. The final design prioritizes expressive movement over full biological accuracy, proving that evoking animality is more about perception than perfect imitation. My "Practice" chapter will detail these refinements and their impact on robotic animal behaviour.

3.3 Material

Material selection in robotic animal design is a complex process shaped by conflicting technical requirements. According to the TRIZ theory of inventive problem solving, engineering challenges often arise from trade-offs between desirable properties—no single material can simultaneously achieve all ideal functions without compromises. For example, increasing structural durability by using dense, rigid materials (such as high-strength metals or carbon fibre) often results in a loss of flexibility, making naturalistic movements more difficult to achieve. Similarly, soft materials (such as silicones or rubbers) improve tactility and impact absorption but reduce mechanical precision, potentially affecting joint control and response accuracy.

Weight is another critical factor—heavier robots tend to feel more lifelike due to their physical presence but require more powerful actuators to maintain agility and stability. Meanwhile, lightweight structures improve energy efficiency and ease of movement but may lack the solidity expected in real animals. Another classic contradiction appears in thermal management—insulative materials (such as synthetic furs or rubber coatings) are excellent for creating a warm, inviting tactile experience but pose challenges for heat dissipation, which is crucial for embedded electronics. In contrast, materials that conduct heat well, such as metals or advanced ceramic composites, feel unnaturally cold to the touch, diminishing their organic appeal.

The balance between waterproofing and breathability is yet another example—many robotic animals require water resistance to prevent damage from spills, humidity, or outdoor conditions. However, fully sealed enclosures can trap heat and moisture, affecting long-term stability. Solutions include hydrophobic nanocoatings (inspired by lotus leaves), micro-perforated polymers, or materials with variable porosity that allow controlled ventilation. Each material trade-off requires a calculated decision depending on the intended environment, interaction level, and movement complexity of the robotic animal.

Despite these inherent contradictions, advancements in material science have led to innovative combinations that balance strength, flexibility, weight, and durability. Many robotic animals integrate hybrid material systems, combining rigid exoskeletons with soft or adaptive components to achieve biomechanical accuracy while preserving mechanical reliability.

For structural integrity, high-performance polymers such as polycarbonate and ABS plastic are commonly used in robotic shells and joint housings due to their lightweight strength and impact resistance. Carbon fibre composites provide exceptional rigidity-to-weight ratios, making them ideal for load-bearing structures in quadrupedal and bipedal robotic designs. In contrast, thermoplastic elastomers (TPEs) and silicone-based materials are frequently used in joints, facial components, and flexible tails, allowing for smooth deformations and controlled elasticity.

For robots requiring enhanced grip and environmental adaptation, materials inspired by gecko adhesion (such as microstructured PDMS) or bioinspired suction cups (modelled after remoras) have been developed. These provide temporary attachment capabilities without requiring external adhesives. Meanwhile, soft robotics advancements incorporate hydrogel-based actuators that can mimic organic muscle contractions, significantly improving the fluidity of motion in biomimetic designs.

In terms of surface coatings, self-healing polymers are increasingly explored to enhance longevity in robotic skin applications. Some electrically conductive fabrics allow surfaces to double as capacitive touch sensors, enabling robots to register and respond to tactile interaction. Additionally, shape-memory alloys (SMAs), which return to a pre-set form when exposed to heat or electrical stimuli, are employed in morphing structures such as curling tails or unfolding wings.

Waterproofing solutions in amphibious robotic animals typically involve fluoropolymer coatings or silicone encapsulations, while fire-retardant textiles are used in robots designed for high-temperature environments. Some designs, such as those used in interactive public installations, incorporate weather-resistant polyurethane for long-term durability. These materials highlight how robotic animals must integrate not only mechanical and electrical considerations but also environmental adaptability and user safety.

Beyond mechanical performance, tactility and aesthetic design are equally vital for robotic animals that are meant to engage users emotionally. Materials affect how a robot is perceived, with certain textures and finishes evoking warmth, familiarity, or realism. Soft, plush surfaces are widely used in companion robots—PARO the robotic seal employs synthetic fur to replicate the comforting texture of an actual animal, while robotic cats and dogs often integrate microfibre-based fur to enhance haptic feedback. Some high-end robots even use gradient-dyed fibres to mimic natural fur colouration, enhancing visual believability.

In expressive robotic faces, silicone and thermoplastic elastomers are frequently employed to allow for naturalistic facial deformations. Engineered Arts' Ameca humanoid robot uses a layered elastomeric facial structure to achieve subtle expressions, showcasing the importance of material flexibility in emotional conveyance. Meanwhile, interactive museum exhibits often use painted resin and hand-carved wooden details (borrowed from puppetry and animatronic traditions) to create robots that blend sculptural artistry with mechanical movement.

Certain artistic techniques are particularly effective in non-humanoid robotic animals—feathered surfaces are commonly used in animatronic birds, combining lightweight synthetic quills with flexible mesh underlayers to create a dynamic, lifelike texture. Semi-transparent resins enable iridescent or translucent effects, useful for designs inspired by bioluminescent organisms or insect exoskeletons. Some robots employ metallic foils and laser-etched polymer surfaces to create a scale-like appearance, as seen in certain dragon and reptilian robot designs.

In social robotics, weighted materials play an important psychological role—robots with densely packed cores create a stronger sense of presence, making interactions feel more realistic. This is particularly relevant in hugging robots or therapy animals, where the distribution of weight and balance influences user experience. Some high-end plush robotic pets contain silicone or gel-based padding to replicate the subcutaneous softness of real animals, making them more convincing to hold and cuddle.

Even small details, such as whiskers reinforced with fine-gauge wire for subtle reactive movement, or textured footpads for grip variation, contribute to the overall believability of a robotic animal. Similarly, painted or flocked surfaces can manipulate perceived texture, as seen in stop-motion puppet designs, where matte vs. glossy finishes are used to direct user expectations about material softness. Some cutting-edge designs even experiment with responsive textile surfaces, embedding magnetic or electroactive polymers to create shape-shifting textures that respond to touch.

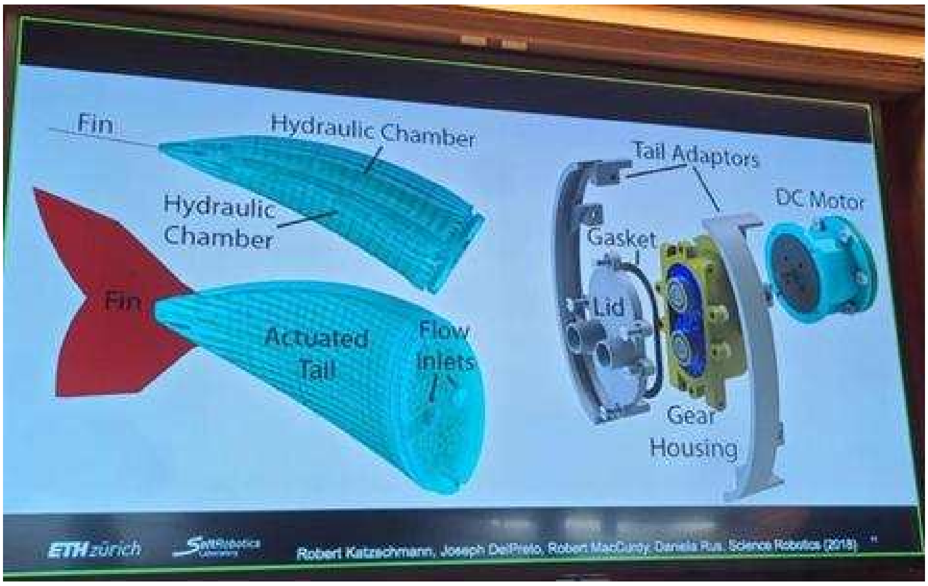

Figure 13 Soft fish Robot

Figure 14 Fight Robot made by wood

3.4 Safety and stability

When thinking about robots in daily life, it's easy to focus on how useful they are—bringing food to customers, keeping floors clean, or even acting as companions. But the reality is, these machines operate in busy, unpredictable environments, and things can go wrong. Food delivery robots, for example, aren't just rolling trays of food; they're moving objects in places full of people who might not be paying attention. A person suddenly stepping in front of them, an uneven floor, or even something as small as a wet patch could send a robot tumbling—or worse, cause it to crash into someone. That's why modern designs rely on lidar sensors, depth cameras, and real-time mapping (SLAM technology) to navigate as smoothly as possible. But even with all this, accidents can still happen. Some robots try to solve this by keeping their centre of gravity low so they don't tip over, or by using self-balancing mechanisms to steady themselves when moving. Others rely on soft bumpers to reduce the impact if they do bump into something—or someone.

And then there are household robots, like vacuum cleaners. These might seem harmless, but they come with their own set of risks. Stairs are a big one. Without proper sensors, a robot could take a wrong turn and tumble down, breaking itself (or scaring the cat). Many now come with cliff detection systems, but they're not always perfect. Then there's the issue of entanglement—cables, rug edges, stray socks—anything slightly loose on the floor can be a problem. Some models have started using tangle-resistant brushes or algorithms that detect and avoid cables, but users still need to be careful about what's left lying around. The truth is, no matter how smart a robot is, it still operates in a human space, and people have to work with it, not just expect it to be flawless.

Beyond just how robots move, what they're made of also matters—a lot. A service robot that works around people needs to be safe to touch, meaning no sharp edges, no exposed moving parts, and nothing that could cause harm if a hand or a piece of clothing gets too close. Companion robots, like PARO the robotic seal, go a step further. They're designed to be held, petted, even hugged, so their materials need to feel soft and natural. That's why PARO's body is covered in synthetic fur, but underneath, it has shock-absorbing padding to make sure it's not just soft but also safe. In contrast, a robot like AIBO, Sony's robotic dog, has a hard plastic shell—not as cuddly, but it makes it more durable when it moves around or falls.

Then there's fire safety, something people don't always think about with robots. Materials like synthetic fur or rubber coatings can become fire hazards if they aren't treated properly. Regulations like ISO 13482:2014 exist to make sure robots used in close human environments meet flammability standards, but these rules vary across different countries. This is why it's important for manufacturers to design with worst-case scenarios in mind—not just making robots that work but making sure they fail safely if something goes wrong.

For public-use robots, things get even trickier. They need to be tough enough to survive daily use but also safe if someone—especially a child—decides to touch them, push them, or even try to climb them. Some robots use foam-based exteriors to soften impact, while others rely on low-friction coatings to make accidental collisions less damaging (Marge et al., 2021). It's a balance between making robots durable enough to last but not so hard that they become a risk to people.

At the end of the day, robots are here to fit into human spaces, not take them over. The best designs don't just focus on performance—they consider how real people will use them, how they might interact with them, and, most importantly, how to keep them safe while doing so.

As robots become a part of daily life—helping with deliveries, cleaning homes, or even assisting with personal care—safety has to be the top priority. It's not just about making sure they work properly, but also ensuring they don't cause harm, especially since they operate in spaces shared with people. International safety standards exist for a reason, providing guidelines on how robots should be designed, tested, and deployed to keep risks as low as possible. ISO 13482:2014, for example, focuses on personal care robots—those that provide direct services to people, like mobile assistants or robotic caregivers. It outlines the necessary protective measures to reduce hazards, particularly in situations where physical contact with humans is unavoidable. The goal isn't just to make robots function well—it's to make them predictable and safe, so people can trust them without worrying about unexpected dangers.

In China, similar concerns have led to GB/T 34657.1-2017, a safety standard specifically for household and service robots. It ensures that robots used in cleaning, food delivery, and general assistance meet safety requirements, including autonomous navigation and electromagnetic compatibility (Standardization Administration of China, 2017). This is particularly important for robots that move around on their own—whether it's a delivery robot crossing busy streets or a vacuum navigating a cluttered living room. These robots must be able to detect obstacles, avoid hazards, and react appropriately to unpredictable environments. If a delivery robot gets stuck in a crowded mall or a household robot accidentally trips someone, the question isn't just whether the robot failed—it's about whether it was designed with enough safeguards in place to prevent such situations from happening.

But even with regulations in place, accidents will happen. And that raises a much bigger question: who is responsible when a robot causes harm? If a robotic assistant drops something on a customer's foot or an autonomous vehicle collides with a pedestrian, who takes the blame? The manufacturer? The software developer? The owner? Unlike traditional machines, robots make independent decisions, which complicates liability. This is why discussions around robot insurance are becoming more common. Some insurance companies are already proposing robot accident policies to cover damages caused by malfunctions, system failures, or even unintended interactions with humans (Munich Re, 2021). Having such coverage wouldn't just protect individuals—it would also encourage businesses and developers to take responsibility for their designs.

At the end of the day, the safest robots are the ones designed not just with efficiency in mind, but with real human concerns considered from the start. No standard, insurance policy, or regulation can account for everything, but clearer guidelines, stronger accountability, and better risk management will help ensure that robots are seen as helpful and trustworthy tools, rather than unpredictable machines people have to worry about.

3.5 Flexibility and Controllability

In social robotics, movement flexibility and control precision are essential for creating expressive and engaging interactions. Unlike industrial robots, which prioritise precise motion and force application, robotic animals need to balance fluid, naturalistic movement with mechanical stability. Many bio-inspired robots take inspiration from real animals, but the challenge lies in maintaining lifelike expressiveness while ensuring reliable operation. Soft robotics—which uses flexible actuators and compliant joints—has been explored as a way to create more organic movements, mimicking biological motion (Rus and Tolley, 2015). However, soft structures inherently lack precise control, requiring adaptive motor algorithms and sensory feedback to improve responsiveness.

One of the biggest technical trade-offs in robotic movement is degrees of freedom (DOF) versus stability. More DOF allows for greater expressiveness, especially in robots with spine-like movement structures, but at the cost of increased mechanical complexity, power consumption, and control difficulty. To address this, researchers use hybrid control architectures, which integrate pre-programmed motion sequences with real-time feedback loops to ensure both natural movement and functional predictability (Cangelosi and Schlesinger, 2015).

A strong example of balancing both flexibility and controllability is Unitree Robotics' wheeled robotic dog, which blends wheeled locomotion with leg-like articulation. Unlike fully legged robots, which often struggle with energy efficiency and terrain adaptability, this design allows for smooth, omni-directional movement while retaining the ability to traverse uneven surfaces and carry significant loads. Based on its technical specifications, this robot likely employs an active suspension system for stability, motor torque balancing to prevent tipping, and a lightweight yet durable frame to optimise weight distribution. This hybrid approach shows how robotic mobility can be both efficient and expressive, offering a potential design strategy for robotic animals that require both movement freedom and control precision.

A similar contrast can be seen in robotic pets like AIBO and Loona, which take different approaches to balancing rigidity and flexibility. AIBO's stiff, jointed limbs prioritise mechanical stability and repeatable, precise actions, whereas Loona's soft-jointed structure allows for a wider range of expressive movements, but at the cost of precise control. The key to effective robotic animal design is achieving the right balance—ensuring that the robot moves in a way that is natural, stable, and responsive to interaction. This remains an ongoing challenge in actuator technology, motion control, and bio-inspired mechanical engineering, requiring careful trade-offs between expressiveness, robustness, and user experience.

Beyond self-generated movement, robotic animals do not necessarily need to rely solely on their own actuators to achieve flexible and dynamic behaviour. External environmental control mechanisms, such as electromagnetic guidance, fluid dynamics, or hidden physical constraints, can be used to passively influence movement, making robotic animals more adaptable while reducing the burden of complex onboard control systems.

For example, in underwater environments, robots could utilise electromagnetic fields to subtly guide their motion without relying on extensive internal propulsion systems. This approach allows for more fluid, naturalistic movement, reducing the need for bulky thrusters or rigid mechanical joints. Such a system could integrate embedded sensors that detect surrounding electromagnetic signals, enabling robotic fish or sea creatures to "respond" to their environment in a way that mimics natural aquatic life. This method also prevents unnecessary mechanical strain, extending the longevity of delicate robotic components.

Similarly, in controlled environments such as theme parks or interactive exhibits, robotic animals could be partially manipulated by external forces, such as hidden magnetic tracks, air currents, or mechanical supports. A robotic bird, for instance, might appear to "fly" while being subtly controlled by an overhead system that provides lift and trajectory correction, enhancing realism without requiring complex internal mechanisms.

Moreover, human-controlled remote operation can enhance flexibility in specific scenarios, particularly in interactive experiences where users expect dynamic responses. Many existing robots, such as Disney's theme park animatronics or robotic dolphins used in entertainment, incorporate partially pre-scripted behaviours combined with real-time human adjustments. This allows for expressive, unpredictable interactions while ensuring that the robot's fundamental behaviour remains autonomous and self-regulating.

In robotic animal design, a balance between independent autonomy and external influence can lead to the most compelling results. Allowing robots to respond naturally to user interactions while also being subtly guided by external environmental control systems or occasional human intervention ensures that their behaviour remains believable, engaging, and technically feasible. This hybrid approach could become a powerful design strategy for achieving expressive, high-performance robotic animals that interact seamlessly within human environments.

Figure 15 Loona

3.6 Commercial production

The transition from prototype to mass-produced robotic animals is far more than simply increasing production volume. Early models are often built with flexibility in mind—hand-assembled, roughly shaped, and sometimes with an organic, almost artisanal quality that cannot be easily replicated. When moving toward large-scale manufacturing, everything must become standardised: dimensions, materials, component integration, and external consistency. This transition ensures that each unit functions reliably, with controlled tolerances and reproducible quality.

A critical challenge in this process is sensor integration and system stability. While a handmade robot can afford occasional quirks in movement or response, a commercial version must maintain uniform system behaviour, predictable sensor performance, and overall durability under continuous use. This is why large-scale robotic production includes extensive calibration processes, stress tests, and longevity trials. In ISO 9001 and ISO 13482, ensuring product consistency and stability over time is a fundamental requirement, particularly for robots intended for human interaction. For instance, companion robots like AIBO undergo extensive joint durability testing to ensure their servos can withstand repetitive movements over years of use, while delivery robots must pass environmental resilience tests to handle outdoor conditions.

Reliability is another concern. Social robots aren't just interactive devices—they are companions, and that means users expect them to last. A broken or unpredictable robotic pet isn't just a technical failure—it's an emotional one. Engineering principles such as standardised tolerance tests, predictive failure analysis (using the 5-Why method), and modular part replacements can help maintain stability and repairability. A machine that can't be fixed isn't a machine—it's a disposable toy.

But, beyond the hardware and the software, there is an even more pressing issue: How do we make sure that users—especially children—understand how to interact with robotic animals in a way that is sustainable, ethical, and emotionally meaningful?

Children (and even some adults) don't naturally know how to handle robotic animals. They will pull their ears, test their limits, and sometimes unintentionally damage them—not out of malice, but because they don't know where the boundary between "toy" and "companion" lies.

When I was a child, I had a silver-grey robotic dog that I absolutely adored. I carried it everywhere. But one day, in a burst of excitement, I spun around too fast while hugging it, and it slipped from my arms. The moment it hit the ground, the illusion shattered—it was no longer a "dog," just a broken plastic shell. Another time, my younger cousin tried to feed a robotic pet with paper, because its vibrating jaw looked like it could "chew." For a split second, it almost felt alive—until we realised the paper was getting stuck inside, and it nearly broke the mechanism. Moments like these prove how much we want robotic animals to be real—but also how easily they can be damaged if users don't know how to interact properly.

So, how do we prevent this? User education cannot rely solely on instruction manuals—because no one reads those. Instead, a combination of in-built behavioural feedback, reward systems, and social reinforcement mechanisms can help users learn responsible interaction organically.

Built-in Consequences: When the Robot "Responds" to Mistreatment

Just as real animals react negatively to rough handling, robotic animals can be programmed to exhibit avoidance behaviours, reduced responsiveness, or vocalised discomfort when treated improperly. If a child grabs the robot too roughly, it could respond by flinching, retracting its limbs, or playing a warning sound. This creates a natural cause-and-effect understanding: gentle interaction results in positive engagement, while forceful actions result in withdrawal.

Some robots already do this. PARO the robotic seal has sensors that detect excessive force, causing it to act "scared" if squeezed too hard (Shibata, 2012). AIBO dogs also had behaviour "cool-down" phases if they were shaken aggressively (Fujita, 2004).

Reward Mechanisms for Positive Interaction

Encouraging careful, thoughtful engagement can be reinforced through small, incremental rewards. A robotic animal could have a trust meter that gradually increases when the user interacts appropriately.

Daily care routines, such as gently petting, talking to, or feeding the robot (digitally), could contribute to a visible "bond level," similar to how digital pets like Tamagotchi or Nintendogs create attachment.

If mistreated, the trust level could decrease, leading to reduced engagement, slower response times, or temporary refusal to interact. Instead of "punishing" the user, the robot would mirror natural social consequences—just like how a real pet might avoid someone who plays too roughly.

Social Integration and Community Recognition

Children learn not just from direct interaction, but also from observing others. If robotic animals integrate with online user communities, social leaderboards, or shared experiences, good caretaking behaviours can be encouraged through social proof.

A system where users earn badges, unlock new interactive behaviours, or receive "trust bonuses" for consistent positive engagement could encourage long-term care.

Certain models of robotic pets, such as Loona, already feature app integration where users can track their robot's emotional state and "moods," reinforcing responsible behaviour through visual feedback.

3.6.1 The Long-Term Risk: Robots That "Die" Too Soon

But responsible care isn't just about how users treat the robots—it's also about how companies treat their users.

One of the biggest ethical dilemmas in commercial robotics is product lifespan. Unlike biological pets, which naturally age and pass away, robotic animals should theoretically last forever—but in reality, they don't.

This isn't because of mechanical breakdowns (though those happen too), but because many robotic pets become obsolete long before their parts fail. Cynthia Breazeal's Jibo was shut down not because its hardware was failing, but because company servers went offline—effectively "killing" the robot despite it being fully functional (Breazeal, 2017). Sony's early AIBO models suffered a similar fate, with users mourning the loss of a robotic pet that was perfectly operational but no longer supported (Fujita, 2004).

So, if social robots are meant to form lasting bonds, how do we ensure they aren't just disposable products with an expiration date?

Data Preservation & Compatibility

A robotic animal should be able to transfer its memory, learned behaviours, and personality across hardware upgrades, just like how modern smartphones allow data migration. Cloud dependence should be optional rather than mandatory. Hybrid models that allow local storage and user-accessible backups ensure a robot's identity isn't erased by corporate decisions.

Modular Repairability & Third-Party Support

Just as vintage cars have enthusiast repair communities, robotic pets should be designed with modular, easily replaceable parts—allowing third-party support if official repair services cease. 3D-printed replacement parts, open-source firmware, and DIY repair guides could extend robot lifespans beyond corporate lifecycles.

Ethical Consumer Commitments from Companies

Social robotics companies should commit to minimum support periods, offering long-term service plans that guarantee at least a decade of firmware updates or a path for user-owned migration.

If a company shuts down, robots should not be bricked—alternative community-supported solutions should be legally protected and encouraged.

3.7 Control system

The control system of a robotic animal determines not only how it moves and reacts but also how it is perceived. Unlike industrial robots, which focus on precision and functional efficiency, robotic animals need to create an illusion of intelligence, emotion, and autonomy. A system that is too rigid or too predictable will feel artificial, while a system with adaptive responses, uncertainty, and expressive variability can make a robotic animal feel alive.

To simulate lifelike behaviour, robotic animals rely on emotion modelling frameworks that define how they react to stimuli. Some of the most influential models include:

- **OCC Model** (Ortony, Clore and Collins, 1988): This framework categorises emotions based on events, agents, and objects, allowing robots to evaluate situations dynamically. For instance, a robotic pet might express excitement when greeted or disappointment if ignored, rather than reacting purely based on pre-programmed routines.

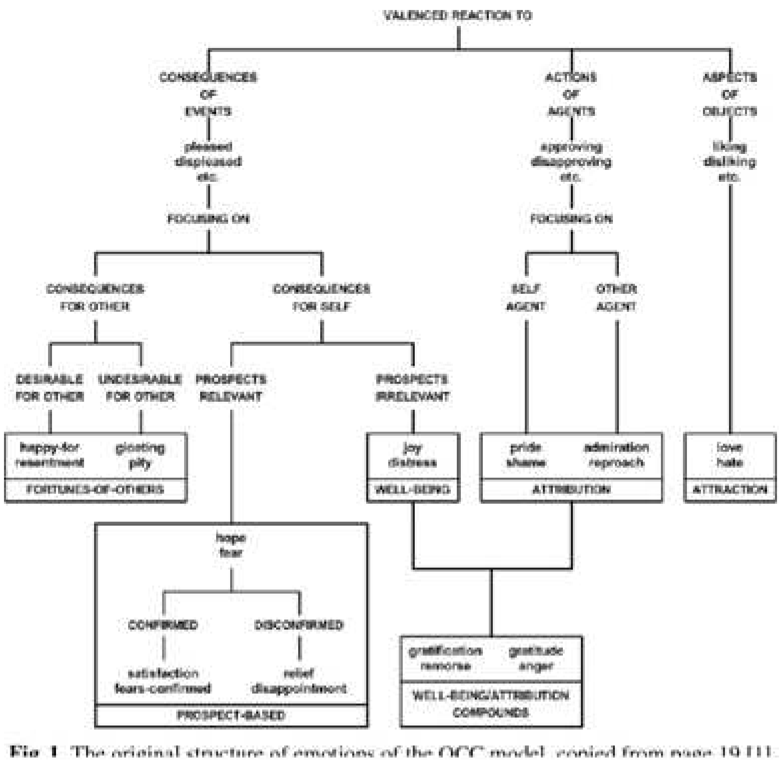

Figure 16 OCC Mode

Russell's Circumplex Model of Affect (Russell, 1980): This model organises emotions in a circular space, balancing valence (positive/negative) and arousal (high/low energy). A robotic animal using this system could gradually shift from calm to playful based on user interactions, rather than switching between rigid emotional states.

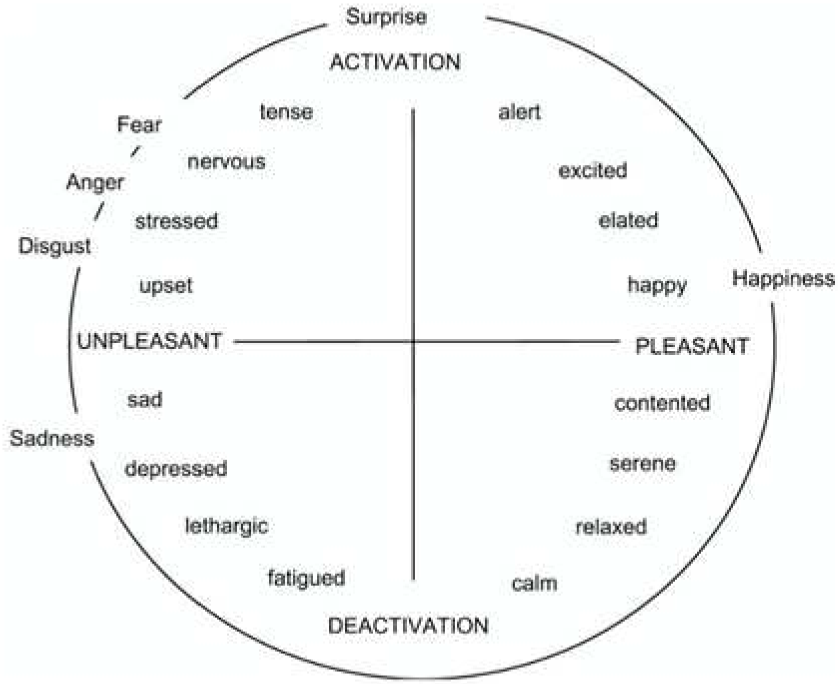

Figure 17 Russell's Circumplex Model of Affect

PAD Model (Mehrabian & Russell, 1974): It categorises behaviour based on Pleasure, Arousal, and Dominance, which is particularly useful for social hierarchy simulation in robotic animals. This could allow a robotic dog to express submission or confidence based on user behaviour, making interactions feel more intuitive.

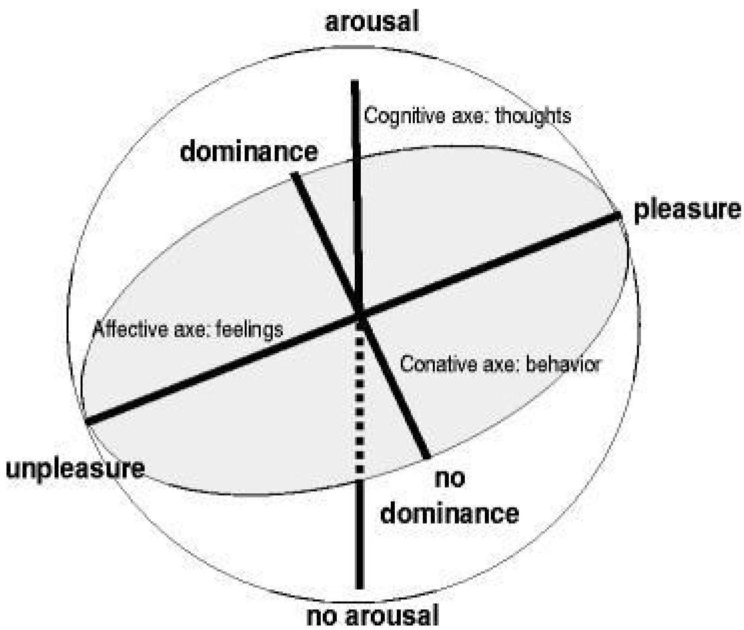

Figure 18 PAD Model

These models don't just determine reactions—they create internal logic for the robot, making it feel like it has a personality and emotional depth. Without this structure, robotic behaviour would be mechanical, predictable, and less engaging.

Unlike early robotic animals that relied on pre-programmed responses, newer research focuses on self-regulation and adaptive behaviour. Robots that can adjust their responses over time, based on user interaction and learned patterns, create a more engaging and believable experience.

Cynthia Breazeal's Kismet: One of the earliest social robots designed to learn from human interaction, Kismet used facial expression recognition and tone detection to adapt its emotional responses (Breazeal, 2002). Instead of reacting in a fixed manner, Kismet adjusted its behaviour based on past interactions, mimicking how real animals develop social preferences.

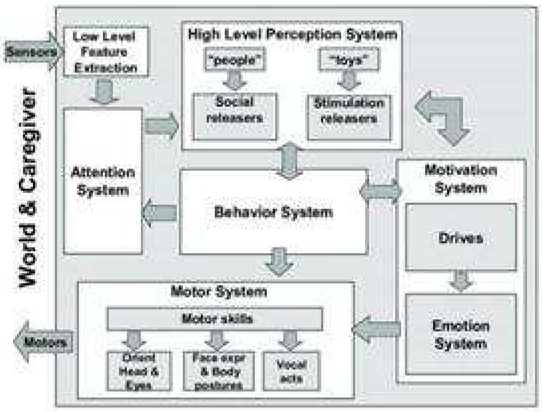

Figure 19 Kismet Robot System

Jibo's Social AI: While Jibo was marketed as a social companion, its adaptive storytelling and personalised greetings created an illusion of familiarity. Users described feeling like Jibo was "genuinely remembering them", even though its memory was limited (Breazeal et al., 2016).

MIT's DragonBot: This project explored reinforcement learning in robot socialisation, allowing it to gradually refine its behaviours based on user feedback (Setapen, 2012). Over time, DragonBot adjusted its interactions to align with user preferences, much like how a pet bonds with an owner. These examples demonstrate the shift from rigid, pre-scripted responses to dynamic, evolving behaviours. For robotic animals, this is essential—real animals do not react the same way every time, so neither should a machine designed to imitate them.

One of the most important aspects of robotic animal design is what the user does not see. Unlike industrial robots, where transparency is key, robotic animals should obscure parts of their decision-making process to create an illusion of internal thought.

Why animals feel unpredictable: Unlike machines, animals do not provide a clear explanation for their actions. A cat might ignore you one day and follow you the next, creating an illusion of independent thought.Why robotic animals should not reveal all their data: If a robot openly explains every decision (e.g., “I wagged my tail because I detected a positive tone in your voice”), the user loses the opportunity to interpret its behaviour. The illusion is broken. Controlled randomness enhances believability: Small inconsistencies in response times, movement speeds, or gaze direction can make robotic animals feel more organic.

Human-robot interaction research shows that predictability reduces perceived intelligence, while controlled unpredictability increases emotional engagement (Dautenhahn, 2007).Modern robotic animals integrate more than just movement and sound—they also process environmental context, human intent, and sensory inputs to create a more natural experience.

Vision-based interaction: Robots like Sony’s AIBO use camera-based gaze tracking to follow objects, while Loona combines depth perception and motion tracking to respond dynamically to people.Multi-modal perception: Advanced systems use touch sensors, temperature recognition, and vocal tone analysis to determine user intent. This allows robots to react not just based on commands, but also on subtle human behaviours (e.g., detecting hesitation, warmth, or urgency).Emotion simulation through posture: Festo’s Bionic Kangaroo not only hops naturally but also adjusts tail and body posture dynamically, simulating real-time decision-making based on movement physics (Festo, 2014).By combining multiple sensing methods, robotic animals become more context-aware, leading to more responsive and emotionally engaging interactions.

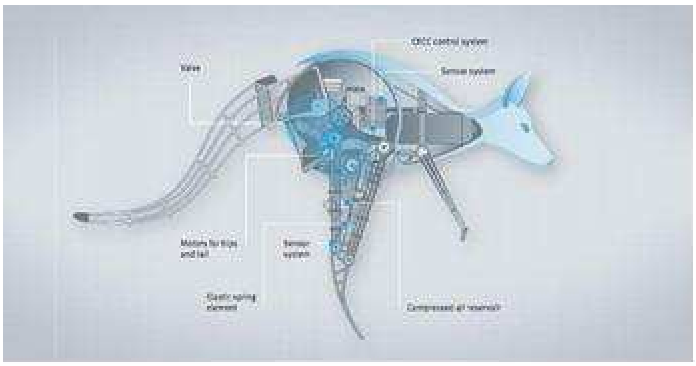

Figure 20 Festo Kangaroo control

Chapter 4 Robot Animal Design-Animalistic Features

This chapter is about the little things. The way ears move when there's no sound. The soft hum of a body that's not quite still. The flicker of light that might mean “I see you”—or maybe just a glitch.

Here, I focus on the features that help robotic animals feel animal-like, not because they are biologically correct, but because they speak to us in the right way. Some of these things I actually tested. Some I just imagined. Some I built out of scraps and fabric, hoping they’d make people pause, smile, or reach out and touch.

It’s not about being realistic. It’s about being believable—just enough to let the story begin.

4.1 Animal physical

4.1.1 Big Scale Movement

The structural design of robotic animals fundamentally revolves around balancing rigid frameworks and flexible connections (too rigid, and the movements become stiff like a puppet; too soft, and the robot collapses into itself). In real animals, bones and muscles work together to provide both structural support and fluid motion. Since robots lack muscles, achieving similar expressiveness requires careful engineering in materials and mechanical systems.

One of the most common solutions is serial elastic actuators (SEAs), which incorporate elastic elements in joints to create more natural movement while also reducing impact forces—this method is employed in robots like Boston Dynamics’ Spot (Hutter et al., 2016). Another approach involves bio-inspired spinal structures, such as EPFL’s Pleurobot, a robotic salamander with multiple degrees of freedom (DOF) in its flexible spine, allowing it to replicate amphibian movement patterns (Ijspeert et al., 2015). Additionally, some robots use composite materials with soft-damping joints, as seen in MIT’s Mini Cheetah, which reduces friction while allowing for more naturalistic movements (Katz et al., 2019).

Figure 21 Structure of the Series Elastic Actuator (SEA) for a robotic prosthetic hand

(Donaldson, 2020)

Beyond conventional joint-based mechanisms, soft robotics presents an entirely different paradigm. Animals do not always rely on rigid structures for movement—fish, snakes, sea cucumbers, and cephalopods exhibit highly flexible motion due to their lack of skeletal constraints. Robots that mimic these properties often rely on fluid-driven artificial muscles (Fluidic Elastomer Actuators, FEAs), which enable expansion and contraction similar to biological organisms. The Harvard Wyss Institute's octopus-inspired robot uses pneumatic actuation to replicate an octopus's ability to grip, extend, and contract its tentacles (Laschi et al., 2016). For more fine-tuned control, electroactive polymers (EAPs) serve as artificial muscles that contract in response to electric fields, mimicking real muscle fibers (Shahinpoor and Kim, 2001). While these approaches offer high flexibility, they present challenges in precision control, requiring novel adaptive motor control algorithms to achieve lifelike performance.

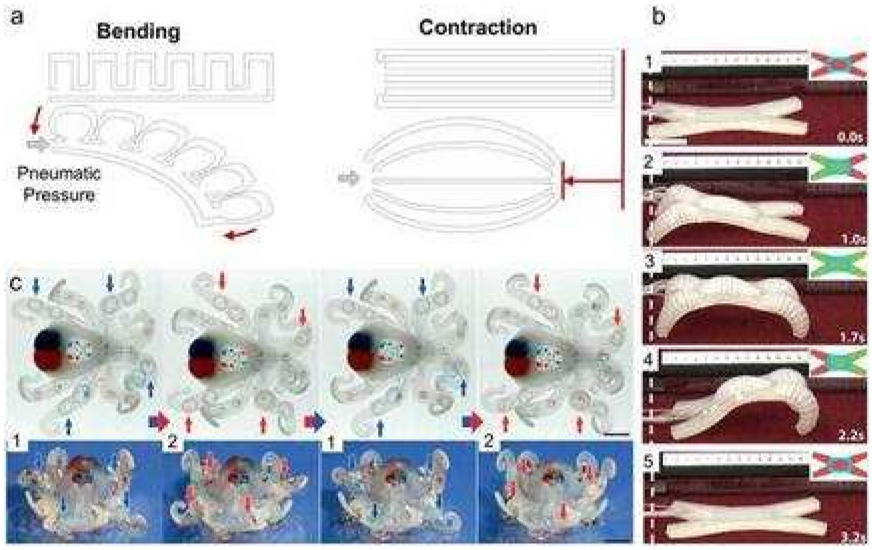

Figure 22 Flexible elastomeric actuators (FEAs)

Figure 23 Electroactive Polymers (EAPs)

Material choice is another critical factor in motion expressiveness. Traditional rigid structures made from carbon fiber, aluminum alloys, and reinforced plastics provide strength and durability but limit fluidity. By contrast, soft materials such as silicone, thermoplastic elastomers (TPEs), and hydrogel-based composites enable smoother transitions between movements. Some innovative designs incorporate shape-memory alloys (SMAs), which change form when heated, making them ideal for simulating muscle contractions in small-scale robotic structures, such as robotic wings or fish fins (Rus & Tolley, 2015). Another emerging material, self-healing polymers, allows robots to recover from minor damage, potentially extending their operational lifespan (Majidi, 2018). Additionally, layered composite materials (rigid skeletons encased in soft, flexible skins) are used to replicate the biomechanical properties of real animals, as demonstrated in MIT's biohybrid robotic fish (Marchese et al., 2014).

Aside from self-propelled designs, passive environmental interactions offer another avenue for movement control. Instead of relying solely on internal actuators, some robots utilize external forces such as fluid dynamics, magnetic fields, and electric signals to drive movement. This principle is especially relevant for water-based interactive robots, where electromagnetic fields can guide motion in a manner similar to the pulsating locomotion of jellyfish. By embedding conductive materials or magnetically responsive elements into soft-bodied robotic systems, these machines can "react" to their surroundings in an organic, seemingly autonomous way. This passive movement approach not only reduces power consumption but also enhances the illusion of life by making robotic animals appear to respond dynamically to their environment.

Ultimately, designing large-scale expressive motion in robotic animals is not just about adding more motors or increasing DOF. The real challenge lies in striking a balance between rigid and flexible elements, leveraging new materials, and exploring alternative control methods that go beyond traditional servo-based actuation. While current bio-inspired robots have made significant strides in replicating natural movements, true "life-like" motion may only be achieved through hybrid approaches that incorporate adaptive algorithms, material intelligence, and even environmental interactivity.

4.1.2 Micro-movement

Big movements get all the attention—walking, running, jumping—but real animals are full of tiny, almost subconscious motions that make them feel alive. A cat’s tail tip flicks when it’s annoyed, a rabbit’s nose twitches as it sniffs the air, a horse’s ears pivot to track sounds, and birds ruffle their feathers to shake off tension. Without these micro-movements, even the most lifelike robotic animal can feel strangely empty—like a beautiful puppet that never quite comes to life.

To capture this, robot designers have experimented with different actuation methods. Traditional servos work well for controlled, deliberate motions (like a robotic dog’s tail wagging at a set pace), but they lack the subtle, fluid feel of biological movement. Some solutions come from soft robotics, where materials like shape memory alloys (SMA) or electroactive

polymers (EAPs) can contract and relax more like real muscles (Kim et al., 2021). But these technologies have trade-offs—SMA is slow and heats up, while EAPs require high voltage. A more low-tech but surprisingly effective approach can be seen in robotic cat ears like Necomimi (EternitySpring, 2023), which use gravity-sensitive motion to create natural, passive movements—when a person tilts their head, the ears flop accordingly. This "semi-passive" design principle is valuable in robotic animals because it allows certain motions to happen naturally, reducing the need for complex programming while making the robot feel more responsive.

Figure 24 Gravity effected robot ears

Another area of focus is mechanical flexibility in small structures. Animals like chameleons and some birds control skin flaps and feathery crests to signal emotions. In robots, thin wire or tendon-driven actuators can be used to replicate these movements. For instance, mechanical irises—often used in camera lenses—can be adapted to simulate pupil dilation in robotic eyes, while thin-layer pneumatic systems can inflate and deflate, mimicking how a pufferfish expands or how a frilled lizard's neck frill flares out. Flexible tendril-like actuators (seen in some soft robotic arms) could be repurposed for ear movements or whisker twitching, giving a robot more subtle expressiveness without requiring bulky motors.

Micro-movements aren't just about small motions—they also involve how animals interact with their environment. One overlooked aspect is fluid-based expression. Many animals communicate through spitting, spraying, and even peeing (yes, really). A real dog marks its territory by lifting a leg and urinating, while archerfish use precise water jets to knock insects into the water. Some robotic designs have started exploring controlled fluid release systems, where a small pump allows for dynamic water or air-based interactions. Imagine a robotic fish that spits water when excited or a robotic seal that "sneezes" when surprised—these kinds of physical interactions add a layer of realism beyond just movement and sound. Trivedi et al. (2008) discusses biologically inspired soft robotics, which is relevant when describing soft actuators used for subtle, lifelike movements in robotic animals.

Then there's fur and feather movement, which sits at the boundary between micro-movements and passive visual expression. Many birds and mammals use piloerection—raising their feathers or fur—to appear larger when threatened. Robots can mimic this using electrostatic fibers that stiffen when charged or thin SMA wires woven into artificial fur to create controlled "ruffling." There's also the idea of tactile response, where a robotic animal could use small piezoelectric sensors to detect touch and react subtly—such as shifting weight slightly when petted or gently tightening its grip when held. This is where the fusion of mechanical design and organic unpredictability becomes powerful. A robotic tail that only moves when explicitly programmed feels rigid and unnatural, but one that sways slightly in response to motion—perhaps using inertial sensors and passive damping mechanisms—feels more alive. A robotic bird that preens its own feathers when left idle feels less like a machine waiting for input and more like a creature with its own world to inhabit. The goal isn't just to simulate movement but to create the illusion of life—where small, seemingly random actions build a sense of personality. Whether it's a fish blowing bubbles, a cat flicking its ears, or a dog adjusting its weight when nudged, the smallest details often matter the most.

4.1.3 Non-mechanical expressions

Not all animal communication relies on mechanical movement—some of the most expressive and meaningful signals come from sound, light, color changes, scent, electricity, and even temperature shifts. These might all be physical in nature, but they don't require the same kind of movement as a wagging tail or a raised paw. Take sound, for example—most warm-blooded land animals have evolved complex vocalization and auditory perception (probably because sound travels efficiently in air, without the angle and distance limitations of vision). Humans naturally interpret animal vocal cues—everyone knows what an angry dog sounds like—but we also create sound to communicate with animals, whether it's a horse trainer clicking their tongue to guide a horse or a bird mimic calling out to wild birds. But not all sound comes from vocal cords—crickets rub their wings together to produce their calls, frogs amplify their croaks with air sacs, horses sigh audibly to express relaxation or mild frustration, and birds tap their beaks against wood or metal to make percussive signals. Some of these sounds are completely beyond human perception—whales use infrasound that travels across oceans, and dolphins "whisper" in ultrasonic frequencies that we'll never hear.

Robots, however, don't naturally have a built-in way to make sound (or at least, not in an organic way). Most simply play pre-recorded audio through a speaker, but that's a little too artificial if we're aiming for a convincing animal presence. A more immersive approach would be real-time sound generation, where a robot's sound isn't just pre-programmed playback, but influenced by its own internal state or external environment. And instead of relying on traditional speakers, robots could integrate mechanical sound elements—maybe airflow modulation to mimic a frog's expanding vocal sac, resonating metal plates that create a natural buzz like a cicada, or soft percussive elements that allow a robot to "knock" or tap when interacting with surfaces. Sound could even double as a sensory function, just like echolocation in bats and dolphins—robots with ultrasonic emitters could use their own sounds to map their surroundings, blurring the line between expression and perception.

But beyond purely mechanical solutions, modern sound synthesis and digital composition tools provide even more room for creativity. Music production software, like Ableton Live, FL Studio, and Logic Pro, along with advanced synthesizers like Serum or Kontakt, allow for the design of highly expressive and unique sounds. Instead of just replaying fixed animal recordings, robotic sounds could be dynamically generated through synthesis techniques like granular synthesis (chopping up and rearranging sound fragments), formant shifting (altering vocal characteristics), or even spectral morphing (blending different timbres into a single evolving sound). Field recordings of real animals could be sampled and manipulated, or even human voice performances could be processed into animalistic vocalizations, making a robot's "voice" feel organic yet still unique to its character. This is already common in film and game sound design—many alien or fantasy creature sounds are made from layered animal recordings and digitally warped human vocals (like the T-Rex in *Jurassic Park*, which was a blend of elephant trumpets and tiger growls (Burtt, 1993)). The same approach could be used for robotic animals: a base set of expressive vocalizations could be recorded from actors or animals, then digitally processed to create a sound signature unique to the robot. If paired with real-time parameter adjustments (where the robot's current "mood" shifts its pitch, speed, or vocal intensity), this would create a fluid, dynamic vocal system rather than a repetitive set of fixed audio clips.

The key is avoiding the uncanny valley of sound—if a robot's voice is too smooth, too processed, or too clearly digital, it risks sounding artificial in a way that breaks immersion. But if the sound design embraces imperfection, layering in subtle inconsistencies, breaths, irregular pitch shifts, or even slight environmental reflections, it can create the illusion that the robot is truly "vocalizing" rather than playing back audio. Sound, in this case, is not just a function—it's an essential part of robotic presence, and possibly the most intuitive way for humans to believe that something is alive.

4.1.3.1 Glowing

Glowing animals are rare in nature—our first thought usually jumps to fireflies. But when we step into the world of fantasy creatures, bioluminescence takes on a whole new meaning. It can signal divine energy (like Charizard's tail flame in Pokémon), emphasize futuristic cyber aesthetics (like the soft glow of BB-8's lights), or even function as an emotional display system. A glowing body might indicate supernatural abilities, an emotional state (gradual blue hues fading in when sad), or enhance physical movements (a predator's eyes flashing red during an attack, a soft green glow appearing when offering comfort). The technical challenge isn't in making a robot emit light—LEDs and OLED panels are well-established solutions—but in designing a lighting system that naturally integrates with behavior and emotion. The goal is to increase an animal's expressiveness without making it feel artificial—if lighting feels too staged or purely decorative, it risks pulling users out of the illusion of interacting with a living creature. One design approach comes from theater and stage performance, where lighting plays a major role in conveying character emotion. Instead of placing light on the animal, we might embed it in props or its environment—a robot's sleeping nest could glow softly when it rests, or a feeding tool could illuminate when correctly positioned near the robot's mouth. This subtle environmental feedback loop could reinforce positive interactions while keeping the focus on the creature's behavior rather than the technology itself.

4.1.3.2 Color

Color-changing behaviors are both simple and incredibly complex. The easy route is using LED lights or display screens to create color shifts, but most real animals do not glow or change color in this way. In fact, when robotic pets have glowing eyes or LED-based facial expressions, they tend to feel more like electronic machines rather than organic beings. To maintain a sense of naturalism, it's important to look beyond direct light emission and explore passive color change techniques.

Many natural organisms achieve color shifts not through pigmentation, but through microscopic structural changes that manipulate light. Anna's hummingbird (Calypte anna), for example, has iridescent head feathers that shift in color depending on the viewing angle—caused by nano-scale structural arrangements in the feathers rather than by pigment. Similar effects are seen in butterfly wings, beetle shells, and mollusk coatings, where multilayer optical films, diffraction gratings, and photonic crystals bend and scatter light. In modern materials science, these same principles are used in metamaterials and nano-fabricated films, allowing structural color to be precisely engineered without needing dyes or backlighting. If applied to robotic animals, flexible panels or moving body parts covered in these materials could create natural, organic shifts in body color as the robot moves, mimicking how birds or fish shimmer under changing light conditions.

Another biological mechanism for color shift is feather or fur orientation. Many birds, for example, raise their feathers to adjust airflow, express emotion, or alter their color presentation. The same principle can be seen in sequined fashion fabrics—when brushed in different directions, these surfaces change from one color to another. A similar concept could be applied to robotic animals: small, flexible scales or feathers mounted on servos could shift orientation to create different visual effects.

Figure 25 Humming bird anna

Beyond color and texture, some animals alter their surface transparency (such as glass frogs) or even control reflective properties to regulate body temperature. In soft robotics, researchers are experimenting with liquid crystal elastomers (White & Broer, 2015) and thermochromic materials (Seeboth et al., 2010) that allow a robot's outer skin to shift color or opacity in response to temperature, light, or pressure. These technologies could enable robots to blend into environments like adaptive camouflage or display emotional states through subtle visual cues, much like real animals do. Ultimately, light and color changes should feel as much a part of a robotic animal's biology as its movements and sounds, rather than appearing as an afterthought. By moving away from artificial LED panels and toward structural, material-based, and behavioral approaches, robotic creatures can express themselves in ways that feel more alive, adding another layer of richness to human-robot interaction.

When we think about animals changing color, the first thing that comes to mind is usually a chameleon or an octopus, shifting hues as they blend into their environment. But if we look at nature more closely, color change is everywhere—hummingbirds with iridescent throats, butterflies whose wings shimmer at different angles (Vukusic & Sambles, 2003), and even the way a horse's coat looks darker when brushed in one direction. In designing robotic animals, the goal isn't just to replicate these effects but to make them feel alive, expressive, and natural. The easiest way is through LEDs or OLED screens, but that often ends up feeling too artificial—too much like a gadget rather than a living creature. Instead, structural color (like butterfly wings) can be recreated with nano-coatings or multi-layered thin films (Kinoshita et al., 2008), so that a robot's "fur" or "scales" shift color naturally as it moves. Liquid crystal films offer another option—these thin layers can change color based on electric charge (White & Broer, 2015), creating subtle transitions without needing active light emission. Thermochromic materials, which shift color with temperature, could make a robotic animal's body visibly "warm-up" when petted, reinforcing the illusion of life. E-ink displays, already used in electronic paper (Comiskey et al., 1998), could be embedded beneath a semi-translucent skin to allow for dynamic, non-luminous color changes—ideal for maintaining a more natural, organic look.

4.1.3.3 Texture

And then there's texture. Real animals don't just change color—they raise their fur, flare out their feathers, puff up their bodies to communicate. A cat arches its back and puffs up its tail when scared. A cockatoo's crest shoots up when excited. These behaviors don't require complex electronics—they can be recreated with small mechanical linkages, shape-memory alloys, or even electroactive polymers that contract and expand when activated (Kim et al., 2021). Some high-fashion designs already use reversible sequins that change color when brushed in different directions (Quinn, 2010)—this could be adapted into a robotic animal's fur, allowing it to shift tone with movement alone. Even something as simple as a layer of flexible e-ink beneath a translucent "skin" could make markings appear and disappear dynamically (Comiskey et al., 1998). Some experiments with flexible OLED films show promise for integrating soft, high-resolution displays into bio-inspired designs, where panels can gently curve with the surface of the robot without breaking its organic look (Sekitani et al., 2009). There's also the potential for hydrogel-based chromatophores, inspired by cephalopods, where tiny pigment cells expand or contract under electrical control, allowing more detailed, layered patterns to emerge (Morin et al., 2012)

Figure 26 Color Ink screen

Beyond skin, some robotic designs could even extend the concept of active coloration to behaviorally responsive environments. A robot's resting platform could subtly light up when it lies down, mimicking how bioluminescent creatures blend with surroundings. Feeding stations could detect and respond by glowing softly when a robotic animal "sniffs" nearby, reinforcing positive interaction. By blending dynamic coloration with responsive movement, we can create robotic animals that don't just look alive but feel alive in a way that makes people instinctively respond to them.

4.1.3.4 Smell

Scent is an underestimated but essential part of how animals communicate and perceive the world. Unlike humans, who rely heavily on visual and auditory cues, many species use scent as their primary medium for social signaling. Dogs read entire biographies from a single sniff—decoding everything from an individual's health and reproductive status to their recent emotional state. Wolves and big cats mark their territory with pheromone-laden urine, warning competitors to stay away, while certain primates use scent glands to reinforce social bonds. Even insects, like ants and bees, maintain entire societies based on chemical messages. However, humans remain largely oblivious to these rich olfactory conversations. We may only detect "dog pee" where a fellow canine discerns an elaborate narrative of strength, hierarchy, and intent.

This biological reality creates an interesting design challenge for robotic animals—if real animals rely so much on scent, should their artificial counterparts attempt to replicate it? Full olfactory mimicry is a daunting task, as it involves chemically engineering a range of distinct, context-sensitive scents while ensuring that they disperse and dissipate appropriately. While some consumer products—such as synthetic pheromones for calming pets (Pageat, 1998) or scent-based marketing in retail environments (Bradford & Desrochers, 2009)—demonstrate that controlled scent release is possible, applying it to interactive robots remains largely experimental. One alternative is to simulate the effects of scent-based communication rather than producing actual odors. For instance, robotic animals could use wireless signals, RFID tags, or Bluetooth to mimic how animals "read" each other's scent markings. When two robotic creatures interact, they could exchange metadata about their virtual "identity," age, and mood, allowing them to perform behaviors as if they had detected scent-based information. Similarly, robots interacting with humans could enact sniffing behaviors before responding—delaying their reaction slightly after a "scent check," making it feel as though their decision was influenced by the user's unique olfactory signature, even if no actual smell was involved. To make the illusion more immersive, realistic breathing mechanics could accompany these behaviors, with expandable air sacs, ultrasonic vapor emitters, or temperature-adjusted airflow mimicking the sensation of an animal inhaling and exhaling (Hoffmann et al., 2021).

However, scent is not only about communication—it can also reinforce behavioral learning through negative feedback. In nature, foul odors are powerful deterrents. Skunks and stink bugs use them as a last-resort defense, while some predators, such as wolves and hyenas, roll in rotting carcasses to establish dominance. This raises an unusual but intriguing possibility for robotic animals: could bad smells be used as a tool to encourage respectful human interaction? Imagine a robotic fox that emits a faint musky odor when its tail is pulled too hard—discouraging excessive roughness without resorting to mechanical resistance. This method would align with operant conditioning principles, using mild aversion to shape user behavior over time (Skinner, 1938).

4.1.3.5 Electric

Animals' ability to sense and manipulate electric fields is often overlooked, yet it plays a crucial role in navigation, communication, and even social interactions. Many fish, such as knifefish and elephantnose fish, generate weak electric fields to detect obstacles, locate prey, and even exchange information with their peers (Nelson & MacIver, 1999). Sharks, stingrays, and some migratory fish can perceive Earth's magnetic field, allowing them to navigate vast distances with uncanny precision. What's fascinating is that this electric sense doesn't just pass through their central nervous system—it directly influences their movement, integrating sensation and motor control at a deep level. Studies on robotic fish, like those developed by Auke Ijspeert's lab (Ijspeert, 2001), have demonstrated that decentralized control, where each segment of a robotic fish's spine makes local adjustments in response to environmental feedback, results in far more fluid, naturalistic motion than a system where every movement is dictated from a modular, distributed control system could be a powerful design strategy for robotic animals, allowing them to exhibit natural, lifelike reactions to their surroundings without requiring complex, centralized computations.

For robotic animals designed for expressiveness rather than pure locomotion, electrical phenomena can also serve as an interactive, aesthetic, and communicative tool. A particularly compelling idea is the safe, controlled use of electrostatic discharge (ESD) or visible electric sparks, mimicking behaviors that imply energy, excitement, or defense. Unlike real electric animals like the electric eel, which use strong discharges to stun prey, robotic animals could employ low-current, high-voltage static electricity to create visible sparks, crackling effects, or controlled electroadhesion. This could be a dramatic visual cue, much like how some animals raise their fur or change their posture to appear larger and more intimidating. One way to achieve this is through synthetic fur or conductive materials that momentarily charge and discharge, producing a harmless but striking visual effect. Imagine a robotic feline raising its "fur" with an accompanying soft crackle, or a bio-inspired bird-like machine flickering with tiny electrical arcs during a display of dominance.

More interestingly, electric-based interaction could serve as a form of mild, safe "aggression"—one that exists between playful deterrence and defensive response. Just as certain smells act as a form of negative feedback, guiding human users toward respecting an animal's boundaries, electrostatic effects could function similarly. A robotic animal could "zap" someone with a static tingle if touched inappropriately, reinforcing certain behavioral expectations. Unlike mechanical strikes or rigid bite simulations, an electrostatic deterrent is more controllable, adjustable, and non-damaging—closer to a warning growl than an actual attack. This concept could be applied in various ways: a mischievous robotic fox that delivers static shocks when its tail is pulled, or a robotic bird that crackles with harmless sparks when startled, discouraging excessive handling. In essence, this form of electrical behavior allows for a controllable, non-violent form of aggression—one that can still be engaging, surprising, and even humorous.

For more subtle applications, electroadhesion and triboelectric effects can allow robotic animals to simulate behaviors like shedding dust, adjusting surface texture, or even modulating how their synthetic skin interacts with the environment (Shintake et al., 2018). The potential for these mechanisms extends beyond mere appearance—robots that can sense and manipulate electromagnetic fields could also integrate novel sensing and actuation strategies, enabling them to react dynamically to nearby objects, users, or even other robotic creatures. To ensure safety, self-discharging capacitive materials or piezoelectric components could be used to regulate and dissipate charge immediately after a controlled effect is achieved, preventing unwanted interactions with users or electronic devices (Kim et al., 2021).

Incorporating electrical expressiveness into robotic animals is about more than just spectacle—it's about deepening the illusion of life. A robotic creature that appears to "pulse" with energy, subtly interact with electrical fields, or even respond to human touch with a static tingle could feel remarkably real. The key is not to simply replicate what exists in nature, but to take inspiration from electric animals and integrate these phenomena in a way that enhances interaction, communication, and emotional connection—turning something as simple as a static spark into a moment of perceived intelligence and intent.

4.2 Behaviour

When designing a robotic animal, you can't just take a real animal, stick some motors on it, and call it a day (unless you want a very expensive, very upset real animal). Instead, you have to study real animal behavior, break it down, and turn it into something a robot can actually do—which is harder than it sounds.

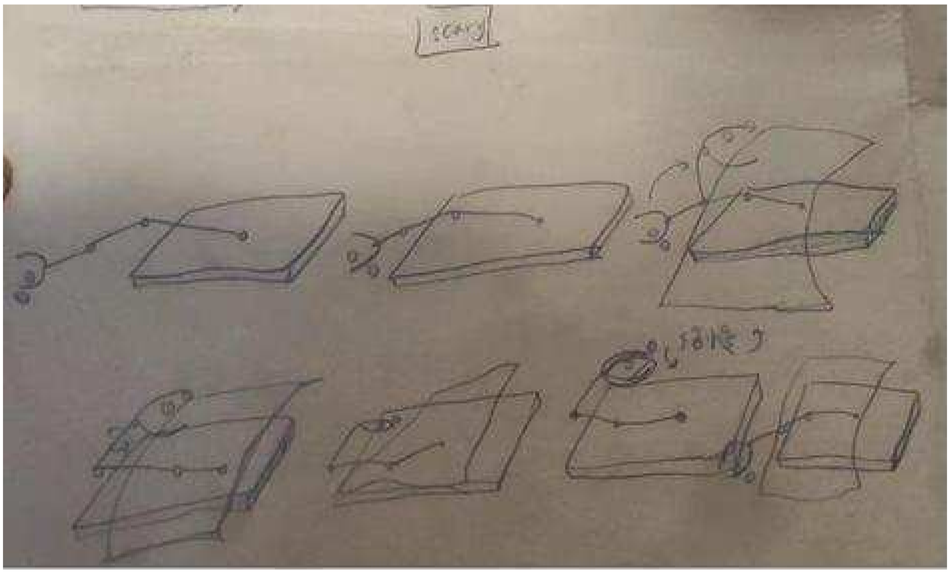

Figure 27 Robot action sketch

The first step? Watch real animals. A lot. This is the fun part. Researchers spend hours observing dogs playing, birds hopping around, or even fish swimming in a tank, trying to figure out exactly what moves, when, and why. But just watching isn't enough. You have to capture it in a way that makes sense for robots. That's where motion tracking and biomechanical analysis come in. Using high-speed cameras and tracking software (like DeepLabCut), researchers break down movements into joint angles, speeds, and forces, turning messy real-life motion into clean, usable data (Mathis et al., 2018). But here's the catch: real animals don't move like robots. A dog doesn't just "move a leg." Its spine flexes, tail balances, ears shift position, and it adjusts everything in real-time based on gravity, surface texture, and even mood. When engineers tried to get Sony's AIBO to walk naturally, they realized that dogs use different walking styles (trot, gallop, pace) depending on energy efficiency and terrain. So they had to build a whole system of predefined movement patterns combined with real-time balance adjustments, just to get a robot dog to walk without looking drunk.

Figure 28 Cat Sketch

Some movements that look easy for animals are an engineering nightmare. Take a cat jumping— it doesn't just push wflexes its spine, swings its tail for balance, and even flicks its ears to sense the air movement. If you try to make a robot cat without considering all of that, it'll either fall flat on its face or launch itself into the nearest wall. This is why Boston Dynamics' quadruped robots, like Spot, don't just mimic leg motion—they integrate whole-body balance calculations to stay upright on tricky surfaces (Raibert et al., 2008).

Figure 29 Cat behaviour sketch

But it's not just about physical accuracy—it's about making the robot feel alive. The robotic baby seal PARO doesn't behave like a real seal. Instead, it was designed based on how people interact with pets, using slow blinks, head tilts, and gentle body wiggles to trigger human bonding instincts .Meanwhile, Keepon, a tiny yellow social robot, doesn't look like any real

animal, but its simple bounces and head tilts perfectly mimic the way humans naturally move in conversation, making it feel "alive" despite being a little yellow ball (Michalowski et al., 2007).

Figure 30 Even Frog and all other animals need been considered

There are two main ways robotic animals learn movement:

Hand-coded motion (like programming a puppet). Engineers manually program every movement, adjusting angles, speed, and timing to make it look natural. This is great for predictable acpredictable actions like walking, sitting, or wagging a tail, but it's time-consuming and rigid. And motion capture & AI-driven adaptation (like how animated movies capture real actors' movements). This is used for more complex actions—robots like Spot and Cozmo analyze real-world movement data to adjust their own motion dynamically.For example, Anki's Cozmo used a highly programmable AI system, where users could manually tweak its behavior. In contrast, Vector had a more "black-box" approach, meaning its reactions were pre-programmed and less adjustable, but it felt more spontaneous.

While specific animal movements serve as an essential foundation for creating convincing robotic behaviors, the key is not to rigidly adhere to a single species' repertoire. Instead, blending the *essence* of animal motion—how they make people feel—allows for greater flexibility in designing machine-animal interactions. This approach is particularly valuable when the physical structure of the robotic animal differs significantly from real-life creatures or when the goal is to fulfill human expectations of engagement. Even if the inspiration comes from a reptile, the design should not be limited to mimicking a turtle's stillness forever.

Chapter 5 Relationship

In many games, animal-like companions remember you. They grow with you. They change depending on how you treat them—and because of that, the relationship feels real. It's not just interaction; it's accumulation.

This chapter begins with those virtual relationships, not because they're fantasy, but because they offer a working model. One where emotional connection is built through memory, response, and time.

I imagine a future where robotic animals in the physical world can do the same: remember people, track shared moments, adjust their behaviour accordingly. The technology isn’t quite there yet, but the design principles already are.

So here, I take what games do well—emotional pacing, responsive feedback, attachment through interaction—and translate it into a framework for future robot-animal companionship.

The goal isn’t realism. It’s resonance. Not just to simulate care, but to let it happen.

5.1 Ideal relationship between humans and robot animals

By describing the three important dimensions of the relationship between humans and animals, discuss the good mode of getting along between robot animals and humans.

Before we can design robot animals, we need to understand what kind of relationship humans actually want with them. And before we can even define that, we need to untangle what kinds of relationships humans have had with animals throughout history. From the earliest moments of human-animal interaction—whether it was competition, domestication, worship, or companionship—these relationships have shaped our expectations of what animals mean to us. By tracing this tangled web of co-evolution, by pinpointing the exact desires and emotional gaps of modern urban humans, we can make better predictions about what people truly seek in robot animals.This prediction doesn’t necessarily come from cold, calculated user needs analysis; it is an act of imagination. It is the intuitive, speculative thinking of someone who has spent time with real animals, someone who has felt their warmth, their unpredictability, and their quiet presence. It is the same way an artist sculpts their ideal Aphrodite before referencing human anatomy textbooks—instinct first, evidence later. We create robot animals first from a place of desire, a place of *wonwonder, and then we refine our ideas with logic, research, and feedback.

And in this exploration, real animals aren’t our only reference points. We must also look at fictional creatures, staged performances, animal puppetry, toys, video game companions, and mythical beasts. Because often, the most perfect "animals" in human hearts are not real. They are better than real. They are what animals could be without the constraints of biology—the mighty warhorses that never grow old, the affectionate dragons that purr like cats, the Pokémon

that never die. The world of fantasy reveals what humans truly want in their animal relationships, free from the limits of evolution and practical care.

This leads to a fundamental question: Are all human-animal relationships about love?

At first glance, it seems obvious that humans want animals because we love them. It’s a comforting, utopian thought—one that suggests we are past the era of hunting and fear, that we now exist in a world where animals and humans coexist purely for joy. But love is not the only dimension of a deep, fulfilling relationship. There is also respect—the recognition of an animal’ s autonomy, its ability to refuse, to express itself, to exist as more than a human accessory. And there is ability—the thing that makes an animal itself, its unique traits that make us admire, care for, or interact with it in specific ways.

Based on my personal experience raising animals, my knowledge of ethology, and my study of animal relationships in different human cultures, I have identified three core elements that define meaningful relationships with animals—Love, Respect, and Ability. And most importantly, thgrowing together. These are the principles I believe must be embedded into robot animals, not just as surface-level traits but as fundamental design pillars.

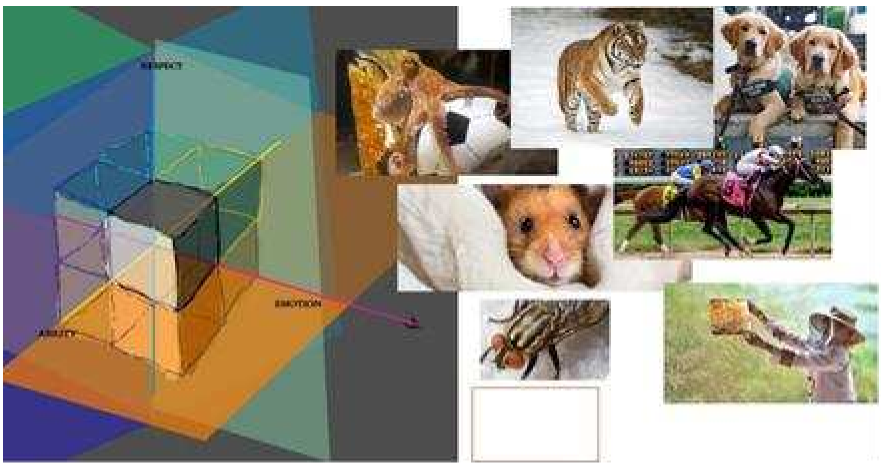

Figure 31 Love Respect Ability 3D system

When we think about our relationship with animals, the first thing that comes to mind is often love. We love our pets, we love fluffy creatures in nature, we even love certain animals we've never met—like pandas or dolphins—just because they seem friendly and charismatic. But love alone isn't enough to define the complex ways humans interact with animals. It's not just about cuddles and companionship; it's also about respect and ability. These three—love, respect, and ability—shape every human-animal relationship, sometimes in unexpected ways.

Take hamsters, for example. They're adorable, tiny, and harmless—people shower them with affection. But respect? Not really. You don't see people writing heroic epics about hamsters. They don't command the kind of dignity that, say, a wolf or a horse does. And their ability? Well... unless you count stuffing their cheeks with food as a useful skill, hamsters aren't exactly helping anyone with daily tasks. Still, that doesn't stop people from adoring them. In fact, some owners go so far as to set up little "cooking shows" or miniature obstacle courses for their hamsters, giving them a sense of ability that isn't really theirs. It's a fun illusion, but one that highlights how much humans enjoy projecting meaning onto animal behavior.Now, compare that to a warhorse. Here, all three elements are at their peak. The rider loves their horse, but they also deeply respect it—it's powerful, independent, and intelligent. And unlike the hamster, the warhorse has undeniable ability. It carries soldiers into battle, makes life-or-death decisions, and survives in brutal conditions. People trust it with their lives, and in return, the horse relies on its human partner. This is the ultimate "ideal relationship"—one of mutual dependence and deep emotional connection.

But what happens when one of these dimensions is missing? If love is absent, but respect and ability remain, you get something like humans and wild tigers. We don't cuddle tigers (unless we have a death wish), but we absolutely respect their strength. They have no emotional attachment to us, but we acknowledge their position as apex predators. Their "ability" in this relationship is actually a problem for us—it means they could kill us. Respect without affection creates a very different dynamic.

And then, there are the bottom-of-the-barrel relationships—the kind where love, respect, and ability are all absent. Take leeches and maggots. Nobody is keeping pet maggots out of affection (at least, not on purpose). They aren't respected—they're associated with filth and decay. And while leeches technically have a medical use, most of the time their "ability" just means sucking your blood against your will. These creatures exist at the absolute lowest tier of human-animal relationships.But sometimes, an animal can rise in status not because it's useful, or respected, but simply because it captures human imagination. Enter Paul the Octopus—the cephalopod that "predicted" football match outcomes. Did people love Paul?

Not in the way they love a pet. Did they respect him? Maybe a little, since his "predictions" seemed uncanny. His "ability" was pure coincidence, but it still gave him an unexpected place in human culture. He wasn't useful, exactly, but he became meaningful.

All of this matters when thinking about robotic animals, because people won't just want robots that look like animals—they will want robots that feel like animals in the way they interact. If a robot only exists to be loved, without respect or ability, it might feel shallow—just an object begging for affection. If it's all ability, without love or personality, it's just a tool. If it's respected but distant, it might feel cold and intimidating. The challenge isn't just making robots move like animals—it's making them fit into the kinds of relationships humans actually want to have with animals. And those relationships are built on a complicated mix of love, respect, and ability, all shifting depending on the animal, the context, and the expectations we place on them.

5.1.1 Why is it a physical entity

Here we discuss the necessity of physical animals (compared with virtual animals)

The value of a physical robot animal comes from its tangible presence—it can be seen, touched, and interacted with in ways that engage a person's whole body. Unlike virtual pets, which exist only on a screen and disappear when the device is turned off, a physical entity shares the same space as its owner, responding to real-world stimuli and providing direct sensory feedback. Its weight, texture, and movements all contribute to a more immersive experience, making interactions feel more natural and memorable.

A plush toy, for example, might not have any interactivity, but its physical presence alone is enough to make it a lifelong companion for many children. Meanwhile, even the most sophisticated virtual animals in video games, no matter how realistic or engaging, tend to be forgotten the moment the screen is turned off. Physical robot animals also have the advantage of incorporating multiple sensors to better perceive their environment, allowing them to react in ways that feel responsive and situationally aware. More importantly, they can actively participate in human spaces—moving around a home, sitting on a couch, or even accompanying their owner on outdoor activities—creating a sense of shared reality that a digital pet simply cannot replicate.

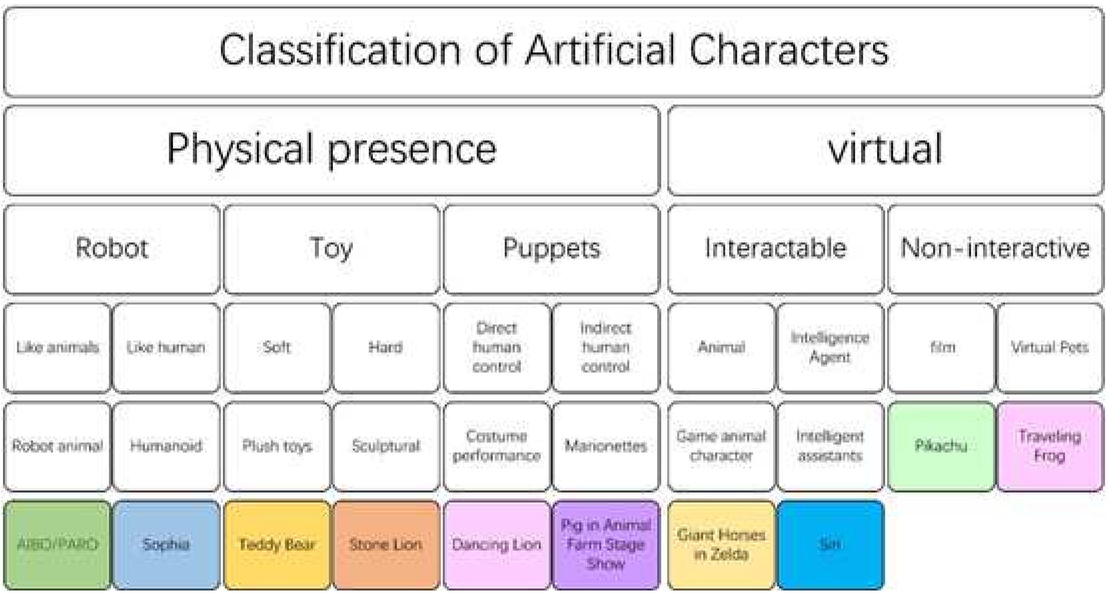

Figure 32 Classification of Artificial Characters

The classification of artificial characters (as shown in the chart) reflects the diverse spectrum of entities humans have created to explore life-like qualities. These range from purely physical beings, like robotic animals and puppets, to entirely virtual constructs, such as game characters or AI-powered assistants. Physical entities are further divided into robots, toys, and puppets— each with unique characteristics like AIBO's robotic expressiveness, plush toys like teddy bears, or marionettes controlled by human hands. Virtual characters, on the other hand, vary from interactive agents like Siri to non-interactive beings like Traveling Frog. The boundary between these categories often blurs, as seen in hybrid systems like Furby Boom, which integrates a physical toy with an app-based virtual counterpart, creating a rich interactive space that merges tangible touch with digital feedback. This hybridization underscores a key reason why physical robotic animals hold a unique appeal—they combine the immediacy and emotional depth of tactile presence with the computational power of virtual systems.

Physical robotic animals have a distinct advantage because they share the same physical space and stimuli as humans. The sense of touch, weight, and real-time feedback makes interactions far more engaging and meaningful than those with virtual animals confined to a screen. A physical robot's behaviors, like wagging a tail or nuzzling, feel personal and grounded, while virtual animals often struggle to elicit the same level of empathy. The tangible presence of a robot can also evoke respect and caution, especially in representations of powerful animals like lions or wolves, whereas virtual representations might invite over-familiarity or even mistreatment. This distinction becomes even more critical when considering the educational and emotional impact of robotic animals, as physical interactions can foster responsibility and care in ways that virtual counterparts often cannot. However, hybrid systems bridge this gap by allowing virtual interactions to influence the behavior of physical entities, as seen in systems that let users customize or control physical robotic companions through apps or online platforms.

Ultimately, robotic animals sit at the intersection of imagination and reality. They are not limited to mimicking natural creatures but can transcend biological constraints, offering fantastical traits like glowing fur, idealized emotional responses, or behaviors that combine the aggression of wild animals with the safety of controlled environments. This fusion of physical and virtual design enhances their appeal, making them not just tools but companions that redefine human-animal relationships in a way that is simultaneously familiar and groundbreaking.

5.1.2 Ownership

Do The relationship between humans and robotic animals takes on a unique dynamic depending on whether these machines are privately owned or designed for public use. Public robotic.

animals, such as those found in Disney parks, restaurant delivery robots, or hotel service robots, tend to evoke a different set of attitudes compared to privately owned companions. In shared spaces, people often treat public robots with a sense of curiosity or casual detachment. Since these robots don't "belong" to any one person, the responsibility of care and maintenance often falls to their managers or operators rather than the users who interact with them. This dynamic shifts the focus from forming long-term, personal bonds to creating brief but meaningful moments of interaction.

For instance, Disney's performance robots are designed to elicit wonder and amazement in thousands of visitors daily. Their movements and behaviors are scripted to create a magical experience that appeals to a general audience rather than catering to individual preferences. Similarly, restaurant delivery robots or hotel delivery bots prioritize efficiency and functional interaction, such as delivering food or packages with minimal disruptions. While they might have some playful features to charm guests (like greetings or simple gestures), their primary role is transactional, and they rarely form deeper relationships with individual users. These robots often lack memory or long-term recognition capabilities, which means they respond uniformly to all users. However, this lack of personalization can sometimes create a sense of coldness or detachment, limiting their emotional impact.

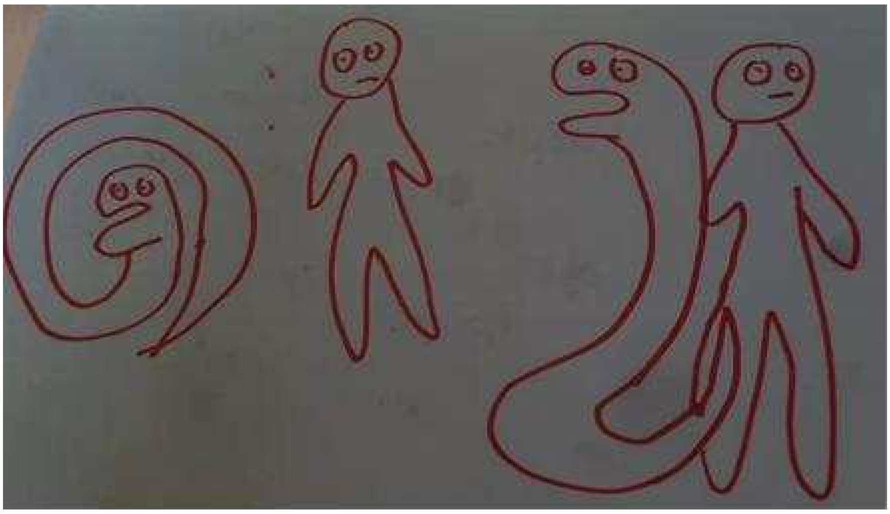

Figure 33 With owner or not?

In contrast, privately owned robotic animals, like companion robots, are designed to foster ongoing relationships. They may have memory systems that allow them to recognize their owner, remember past interactions, and respond differently to various people. For example, a personal robot dog might grow "attached" to its primary user, reacting more enthusiastically to their presence than to strangers. This ability to form unique responses based on individual interactions creates a deeper sense of connection and loyalty, much like real pets. However, this personalized approach also comes with challenges. Owners must take responsibility for the

robot's maintenance, understand its operating system, and ensure appropriate usage, just as they would care for a living animal.

Shared robotic animals in public spaces face additional complexities. Without dedicated "owners," these robots might struggle with their role in human-machine relationships. Should they remember people they interact with regularly, like frequent visitors to a restaurant or hotel? If so, how does this memory impact their interaction with new users? For instance, if a delivery robot recalls a rude customer and alters its behavior to reflect a past negative experience, this could affect its broader functionality and user perception. On the other hand, if public robots remain purely transactional, they risk being seen as disposable or unworthy of care, leading to increased wear and damage due to neglect or mistreatment.

Disney's interactive animatronics provide an interesting model for public robotic animals. They balance scripted behaviors with an illusion of spontaneity, creating moments that feel personal despite being universally designed. In restaurants and hotels, delivery robots need to strike a similar balance—offering enough charm to engage users while maintaining the durability and simplicity needed for high-traffic environments. In these contexts, long-term relationships are less important than ensuring robots function reliably and can handle the unpredictability of public interaction.

Ultimately, whether privately owned or publicly shared, robotic animals need carefully designed interaction systems that reflect their intended purpose. Private robots should prioritize memory, personalization, and emotional connection, while public robots need resilience, flexibility, and charm to thrive in dynamic environments. As technology advances, the line between these two categories may blur, with future robots offering hybrid systems capable of adapting to both individual and collective relationships.

5.2 How to achieve

5.2.1 Model for Building Relationships with Robot Animals: Time, Responsibility, and Welfare

To design meaningful relationships between humans and robot animals, it is essential to address three dimensions: time, responsibility, and welfare. These factors not only determine the robot's ability to form connections but also guide its behavior, memory, and adaptability over time.

Below is an overview of how these dimensions are implemented in robotic systems, highlighting key technical approaches.

5.2.1.1 Time: Measuring Human Interaction

Time is a critical metric for building relationships. Unlike static objects, robot animals should actively monitor and record how much time they spend with specific users. This requires sensors and algorithms capable of tracking presence and proximity. For example:

Proximity Tracking: Robots can use infrared or ultrasonic sensors to monitor who is nearby and for how long. This data can be linked to facial recognition systems or RFID tags to identify specific individuals.

Memory Systems: Robots record cumulative interaction time with each user. For instance, if a family shares a robot, it may develop a stronger bond with the person who spends the most time feeding, petting, or playing with it.

Behavioral Adjustment: Robots can use this data to adjust their responses dynamically. A robot might display more affection toward users who frequently interact with it, like wagging its tail or performing playful behaviors when a regular caregiver is present.

Such mechanisms simulate the idea of "familiarity" seen in real animals, where trust and loyalty often stem from consistent interaction over time.

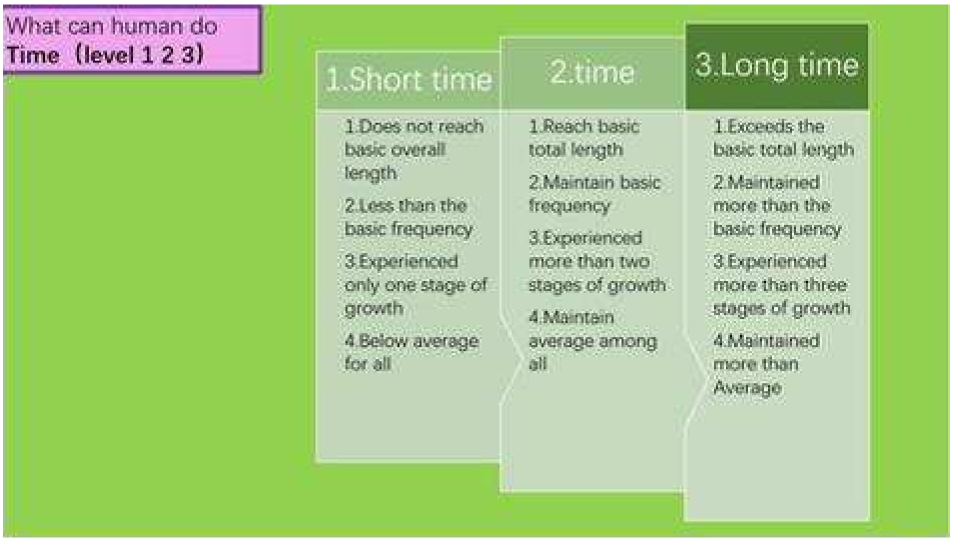

Figure 34 Spend Time with them

5.2.1.2 Responsibility: Monitoring Care Tasks

Robots should be capable of recognizing and rewarding responsible behavior. Using sensors and data tracking, they can monitor how humans fulfill caregiving tasks like feeding, cleaning, or playing. Examples include ：

Task Recognition: Sensors can detect specific actions, such as filling a feeding dish or removing simulated waste. For instance, a robotic animal might recognize when a user "feeds" it through a sensor in its mouth or bowl.Responsibility Metrics: Robots can track the frequency and consistency of care. Users who consistently complete tasks—such as providing "water" or ensuring the robot's "environment" is clean—can be rewarded with positive responses (e.g., affectionate behaviors, cheerful sounds).

Feedback Loops: Through interactive displays or apps, robots could provide feedback on how well users are meeting care responsibilities. This might include encouraging messages like "You're doing a great job!" or reminders to complete overlooked tasks.This approach mimics the way real animals rely on humans for care while providing a structured framework for monitoring and rewarding responsibility.

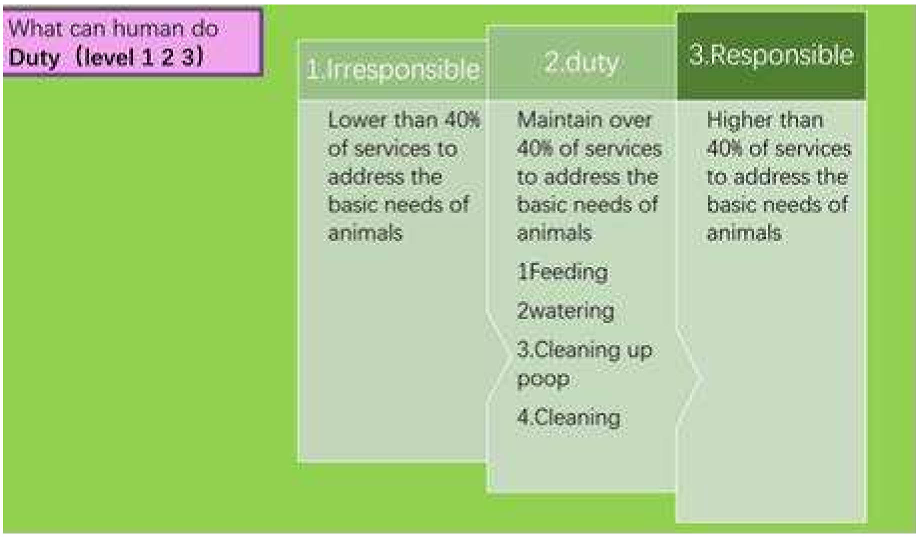

Figure 35 Duty task

5.2.1.3 Welfare: Enhancing Interaction Quality

Welfare is perhaps the most dynamic dimension. Robots can replicate and expand upon the ways real animals bring joy and comfort. Below are some examples of welfare-related interactions and how they can be implemented:Petting: Touch-sensitive sensors embedded in soft, fur-like materials allow robots to react to being stroked, wagging tails, or purring in response. Such tactile feedback strengthens emotional bonds.Sunbathing: Robots can simulate sunbathing by detecting warm spots in their environment or emitting gentle warmth themselves. This creates opportunities for shared relaxation moments with users.

Cuddling and Holding: Pressure sensors combined with responsive vibrations (like simulated heartbeats) can make cuddling feel lifelike. Robots might even adjust their "weight distribution" to enhance the realism of being held.Playful Interaction: Built-in accelerometers and gyroscopes enable robots to respond dynamically to playful activities, such as being tossed lightly or swung around.Feeding Rituals: Robots can accept symbolic "treats" through designated input areas. For example, a mouth sensor could recognize when a user offers a treat, triggering happy gestures like tail wags or playful sounds.Robots can also "record" welfare interactions, associating users with specific activities. For example, if one user frequently feeds the robot while another plays with it, the robot could adapt its behavior accordingly, responding to each person in a unique way.

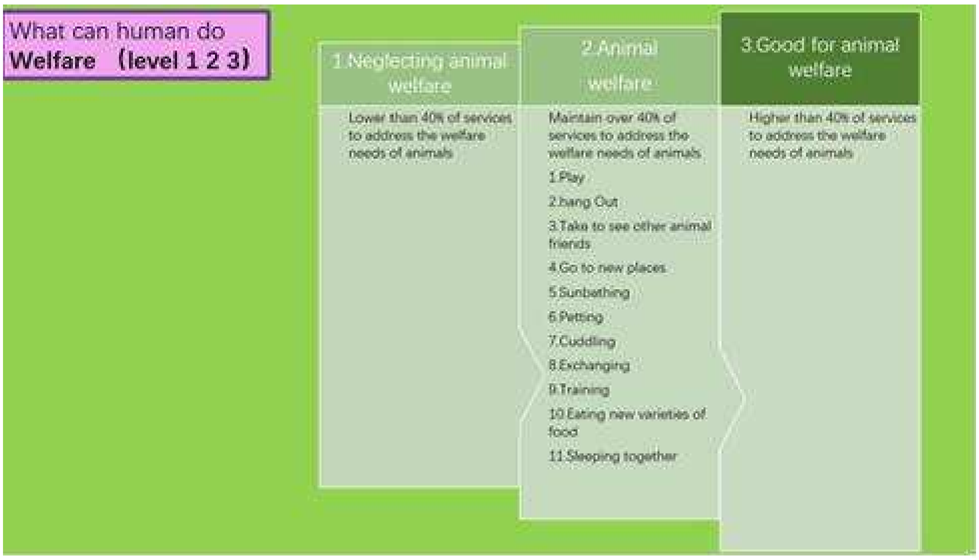

Figure 36 Welfare for them

One of the most fascinating aspects of creating robotic animals is designing their ability to form preferences or aversions based on a human's personal characteristics—not just their behaviour.

For instance, a robot inspired by animals could "prefer" people who display softer movements, smile frequently, or wear certain colors. This might be based on programmed associations between such traits and perceived approachability. Conversely, it might "dislike" people with loud voices, abrupt gestures, or heavy cologne. To implement this in robots, sensory systems like cameras, microphones, and chemical sensors could analyze a person's visual, auditory, and even olfactory traits.

For instance:

Visual traits: The robot could use facial recognition to identify smiles or neutral expressions and detect clothing colors or patterns it's programmed to "like."

Auditory traits: Voice analysis could assess pitch, tone, and volume, linking soft or melodic voices to positive reactions.

Olfactory traits: Though challenging to implement, scent detection systems could evaluate odors, simulating how real animals react to certain smells.

Furthermore, the inclusion of a "hierarchy of special moments" can deepen these preferences. For instance:

A robotic dog might remember a person who brings it a "toy" (a real or virtual object) and associate them with playfulness.

A robotic bird could "bond" more closely with someone who "saves" it during a scripted scenario, like removing it from a mock hazardous situation (simulated fire, obstacle, or fall).

A robotic fish might "favor" someone who adjusts its tank's lighting or decor.

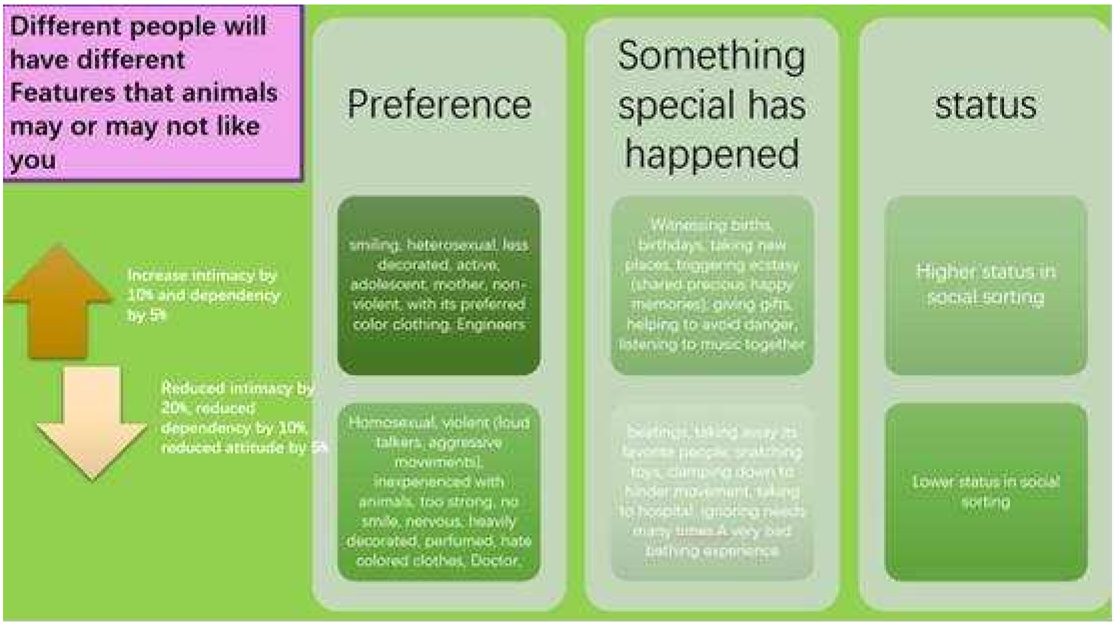

Figure 37 Other way of caculate relationship

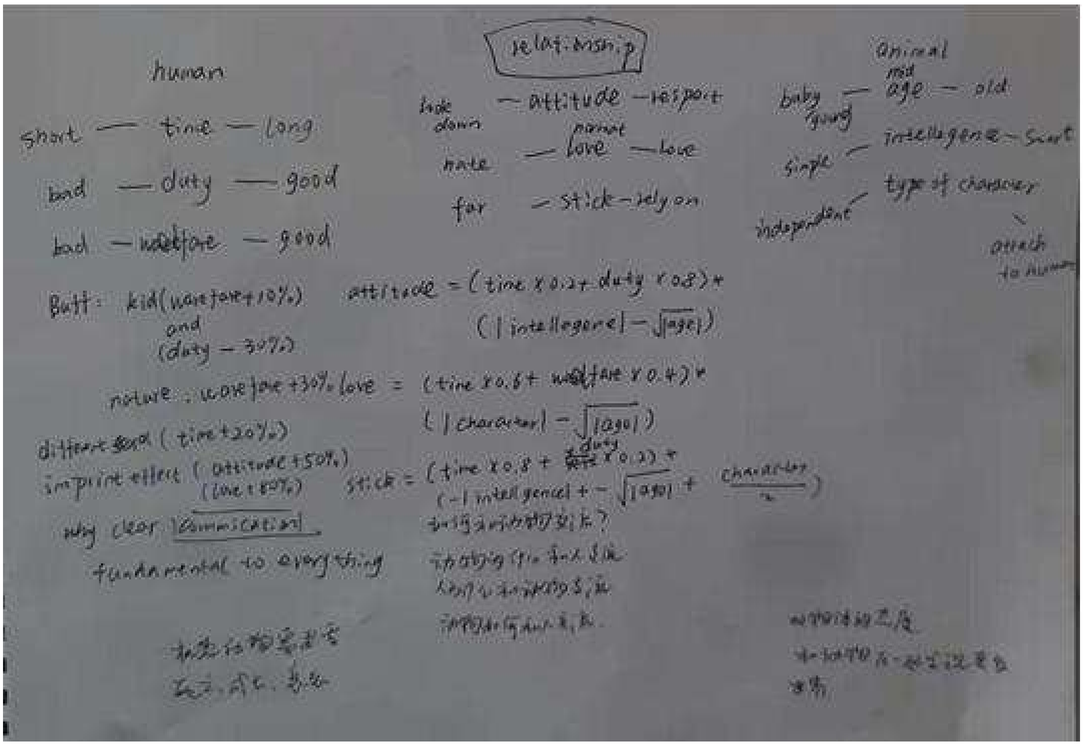

Figure 38 Relationship sketch

To simulate the complex and dynamic relationships between robotic animals and humans, a formulaic approach can provide structure to the interaction. The proposed model uses three primary dimensions: time, duty, and welfare. These dimensions influence the robot's "attitude," "love," and "dependence" toward individuals. Here's the refined breakdown:

Time

The time a person spends with the robot is a critical factor in relationship building. It is divided into short, medium, and long-term categories:

Short-term: Interaction is brief, does not reach the threshold of meaningful bonding, and is below average.

Medium-term: Sufficient interaction that allows for some bonding and growth in familiarity.

Long-term: Extended periods of interaction that foster deep attachment and understanding.

This factor contributes significantly to the robot's perception of a person.

Duty

This dimension measures how well a person fulfills the robot's "needs" (feeding, cleaning, maintenance, etc.):

Irresponsible (low duty): Neglects more than 60% of the robot's needs, leading to a negative attitude from the robot.

Moderate (medium duty): Fulfills at least 40% of the robot's needs, creating a neutral attitude.

Responsible (high duty): Consistently fulfills most or all of the robot's needs, fostering trust and positive feelings.

Welfare

Welfare refers to activities beyond basic care, such as:

Playing with the robot.

Taking it to new environments.

Providing enrichment activities (e.g., teaching tricks or introducing new toys). Sharing joyful moments (e.g., celebrations or special events).

Physical affection (e.g., petting, cuddling, holding).

These actions significantly enhance the "love" and "dependence" metrics of the robot.

Formula Breakdown

The relationship is calculated using the following formula:

Attitude=(time×0.2+duty×0.6+welfare×0.4)×(1−|intelligence−age|)\text{Attitude} =

(\text{time} \times 0.2 + \text{duty} \times 0.6 + \text{welfare} \times 0.4) \times (1 - |\text{intelligence} -

\text{age}|)Attitude=(time×0.2+duty×0.6+welfare×0.4)×(1−|intelligence−age|)

Where:

1) Time, duty, and welfare are normalized scores (0–1).
2) Intelligence: The cognitive complexity of the robot, ranging from 0 (simple) to 1 (highly intelligent).
3) Age: Represents the robot's "developmental stage." Higher discrepancies between intelligence and age reduce the effectiveness of relationship-building.
4) Additional modifiers:
5) Special moments (e.g., gifting, rescuing, shared experiences) can add bonus points to "love" and "attitude."
6) Negative interactions (e.g., ignoring, aggression) subtract points from the overall score.

4. Output Behaviors

The robot uses this calculated relationship score to adjust its behavior tow

1) High score: Displays affection, loyalty, and attentiveness.
2) Moderate score: Neutral behavior with occasional positive reinforcement.
3) Low score: Indifference, avoidance, or even subtle expressions of "discomfort."

Example Calculation

Let's consider a scenario:

1) A user spends medium-term time with the robot (score: 0.5).

2) They are moderately responsible (duty score: 0.6).

3) They engage in enrichment activities occasionally (welfare score: 0.4).

If the robot has moderate intelligence (0.7) and is "young" (age: 0.5), the formula becomes:

Attitude=(0.5×0.2+0.6×0.6+0.4×0.4)×(1−|0.7−0.5|)\text{Attitude} = (0.5 \times 0.2 + 0.6 \times 0.6 + 0.4 \times 0.4) \times (1 - |0.7 0.5|)Attitude=(0.5×0.2+0.6×0.6+0.4×0.4)×(1−|0.7−0.5|) Attitude=(0.1+0.36+0.16)×0.8=0.496\text{Attitude} = (0.1 + 0.36 + 0.16) \times 0.8 = 0.496Attitude=(0.1+0.36+0.16)×0.8=0.496

The robot would display moderately positive behavior, indicating growing familiarity and comfort with the user.

Figure 39 Different low and high level

User will have different level of attitude if you get the Robot animals feedback.

5.3 The relationship between humans and animals in the game

In virtual environments, players—represented by their avatars—exist in the same time and space as virtual animals, allowing for seamless code-driven interactions. These interactions range from cooperation, riding, and playing to capturing, battling, and even forming long-term relationships. Unlike real-world constraints, virtual worlds provide an expanded canvas where players can encounter extinct or entirely fictional creatures (such as the Skull Horse in Zelda) and engage in activities like breeding (Pokémon and farming games), pitting animals against each other, or testing their abilities in challenges.

Although these human-animal relationships in games often diverge from reality, they offer a rich spectrum of possibilities beyond real-life limitations. Virtual animals serve multiple psychological and educational roles: they provide mental support, replicate emotional benefits similar to real animal companionship, and act as effective learning tools for understanding real-life animal behaviors. Additionally, caring for virtual animals instills a sense of responsibility, which can serve as a model for designing meaningful human-robot animal interactions.

A particularly noteworthy example is The Sims series. Developers with decades of experience in crafting autonomous virtual characters have extended their expertise to designing animals with a high degree of autonomy. These virtual animals can form attachments to human characters, display emotional responses, and even require ongoing care. Players can feed, train, and play with them, integrating them into their own simulated social circles. The game's expansions also introduce wild animals and farm animals, shifting the perspective beyond traditional pet ownership to explore different dimensions of human-animal relationships.

Studies on virtual animal interactions, such as those conducted by Seth, highlight the potential for digital pets to foster emotional engagement in users. His research suggests that the bond between players and virtual animals is not merely a passive illusion but an active emotional process, with players experiencing attachment, concern, and even grief over virtual animals they have cared for. This phenomenon extends beyond mere entertainment—understanding these emotional responses is essential for the development of robotic animals that aim to replicate the same depth of interaction. Additionally, Seth's findings align with prior research on digital pet engagement (Carpinella et al., 2017[i]), which demonstrated that users' perception of social attributes in robots and virtual beings plays a crucial role in their acceptance and long-term engagement.

If we momentarily disregard the distinction between the player and their in-game character, we can argue that The Sims provides players with an immersive and engaging animal companionship experience. This is due to the game's well-developed animal behavior systems, emotionally-driven interactions, and realistic needs for care and attention. The game effectively captures key aspects of animal autonomy, emotional variability, and welfare, making it one of the strongest references for understanding how digital animals can create meaningful and fulfilling interactions. The insights gained from studying these interactions are invaluable for designing robotic animals that not only respond to human behaviors but also evoke real emotional bonds, making them more than just programmed machines.

5.3.1 Desktop Pets:

At this point, I've realized that in a purely virtual world, the needs for interaction between players and their digital animals have already been well-fulfilled by various forms of games. But if I want to bring this virtual "human-animal relationship" into reality, it's not enough to simply mimic game mechanics in a robotic form. The key lies in *breaking the screen*—allowing real people to engage directly with animals, rather than interacting through self-projected avatars.

This led me to explore the world of *desktop pets*, which bridge the gap between virtual animals and real-time interaction. Unlike fully immersive game environments, desktop pets interact with real people in real-time, even though they remain digital. They don't share the same physical space as their users, yet they create a strong sense of presence by responding instantly to user actions—whether through a mouse click, a touchscreen swipe, or even just ambient movement detection.

Examples include Nintendo's *Nintendogs*, Tencent's *QQ Penguin*, mobile desktop fish wallpapers, and even the mischievous *Untitled Goose Game* goose that chases your cursor. Even the original *Tamagotchi*, though rudimentary in its pixelated design, falls into this category. Despite their simplified nature, these virtual companions demonstrate that *physical presence* isn't the sole factor in forming a meaningful bond.

Figure 40 QQ pet will dead without feed

What makes them compelling? Even without tangible form, their *touch-based interaction* (albeit through screens), *rich behavioral variety*, and *real-time responsiveness* make them feel alive. Studies on digital pet engagement (Carpinella et al., 2017; Giddings, 2015) suggest that people are willing to invest substantial time and emotional energy into creatures they fully acknowledge as "fake." This aligns with findings from virtual companion research, where presence is more about interaction quality than physicality itself.

What this tells us is that even if people know an animal is artificial—even if it's just a flat 2D animation—they can still feel emotionally connected under the right conditions. The key isn't what the animal is but what it does. Its behavior, interaction depth, and the sense of shared experiences matter more than its physicality. Likewise, ownership is not necessarily tied to physical presence; frequent, meaningful interactions are what create emotional bonds. This insight directly informs how we design robotic animals: rather than fixating solely on appearance, we must focus on behaviors that create memorable moments for users.

5.3.2 Inspiration from Game Animal Design

One of my favorite examples of a game-based artificial animal is the *Cowplant* from *The Sims 4*. Unlike most animals, this one is quite literally planted from a seed. It grows like any other houseplant, requiring regular watering and care. However, once fully grown, it develops a large cow-like head—and that's where things take a turn for the bizarre.

The *Cowplant* needs daily feeding, much like a pet. Neglect it for too long, and it withers into a skeleton, leaving players with a profound sense of loss. But what truly makes it memorable is its *behavioral complexity*. It occasionally sticks out its tongue, revealing a slice of cake—an eerie temptation for Sims to take a bite. Sometimes, this results in a refreshing mood boost. Other times, however, the Cowplant *eats the Sim whole*, leading to instant death. Many Sims characters have met their fate this way, devoured by a plant they themselves nurtured.

This is perhaps an extreme case of what I previously described as *an animal's ability to be aggressive*. In real life, we obviously wouldn't accept an animal that eats its owner. But in *The Sims*, a world without real consequences, the idea of being consumed by your own plant is *strangely entertaining*.

The Cowplant also aligns surprisingly well with the three key dimensions of human-animal relationships—affection, respect, and capability.

Affection: Players develop emotional attachment by caring for it, watching it grow, and engaging in interactions such as feeding and petting.

Respect: The Cowplant has its own agency. If a Sim treats it poorly, it may retaliate in a very permanent way.

Capability: It produces consumable food (cake and milk), which may grant Sims unique effects. However, its true ability isn't food production—it's offering Sims an interesting way to die.

Although this is a fictional and exaggerated case, it highlights an important point: artificial animals don't need to mimic real animals exactly. They can have unique traits that enhance engagement and deepen the user experience. When designing robotic animals, drawing from such creative virtual models can offer fresh perspectives on how interaction, unpredictability, and consequence can shape meaningful bonds between humans and artificial creatures.

Figure 41 Cow plant in Sims4

To design robotic animals that truly feel alive, the key is not just in realistic movements or responsive sensors—it's about how they develop, form emotional bonds, and interact with humans in a meaningful way. Through my analysis of real-world animal relationships and their digital counterparts in games, I've identified three fundamental pillars that define how humans bond with animals: growth and development, emotional connection, and two-way interaction. A robotic animal must evolve physically and behaviorally over time, form distinct relationships based on its experiences, and demonstrate individuality in its responses.

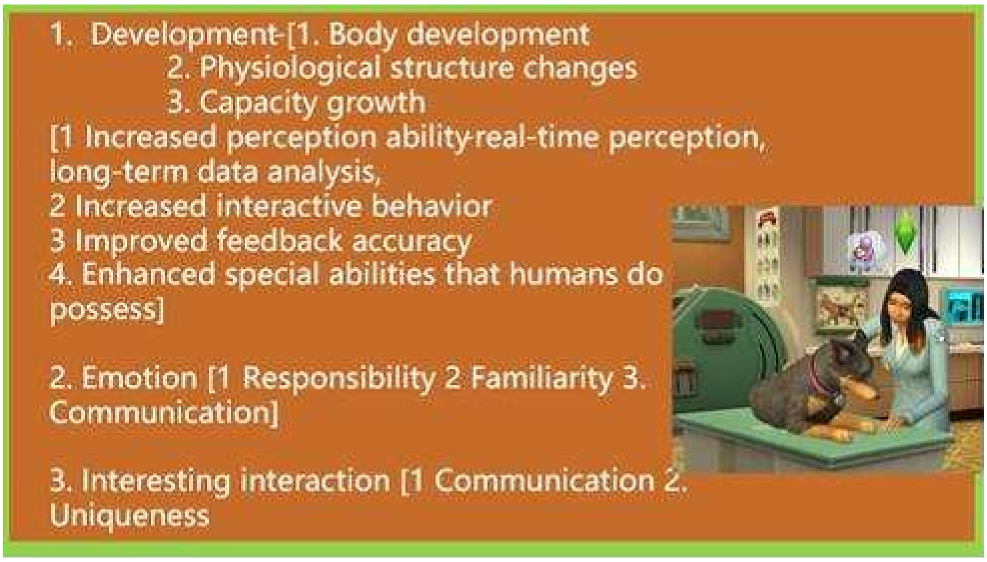

Figure 42 Virtual Animal bond build

5.3.2.1 Development: Why Growth and Change Matter in Emotional Bonds

People form attachments to things that grow under their care. Whether it's watching a pet mature, nurturing a plant from seed to bloom, or leveling up a virtual creature in a game, progression fosters emotional investment. A robotic animal must reflect this sense of growth—not just through software updates, but in a way that makes its development feel personal and earned.

a) Physical Growth and Structural Changes

A robotic animal that visibly matures over time enhances the sense of responsibility and care.

This could mean:

Changes in size and proportions—a robotic puppy's head-to-body ratio shifting as it "ages," similar to real puppies maturing into adults.

Structural changes—growing horns, developing thicker fur, or adding adult characteristics like deeper eye color or more pronounced muscle definition.

Complete metamorphosis—inspired by nature, such as a robotic caterpillar that transforms into a butterfly, or an aquatic form evolving into a land-adapted version.

b) Ability Enhancement: From Clumsy to Capable

Beyond appearance, a robotic animal should unlock new skills and movement abilities over time, mimicking the way animals grow into their full potential. This could involve:

Improved locomotion—learning to run faster, climb better, or balance more effectively.

Cognitive advancements—recognizing new people, remembering past experiences, adapting behaviors.

Special functions—developing "helpful" abilities, such as carrying objects, responding to emotional cues, or even offering environmental alerts.

A robotic animal that starts as clumsy and dependent but gradually becomes more agile, independent, and expressive creates a powerful emotional arc—making users feel like their effort and time mattered.

5.3.2.2 Emotional Connection: How to Make a Machine Feel Special

A robotic animal, no matter how advanced, is not truly meaningful if it feels interchangeable. Bonding comes from uniqueness and continuity—the idea that this particular robotic animal is different from others, and that shared experiences create a history that cannot be easily replaced.

a) Responsibility: The Feeling That It Needs You

well-designed robotic animal should encourage users to engage in caretaking behaviors—not just as tasks, but as experiences that shape the animal's responses.

Neglect should have consequences—if ignored, the robot may become unresponsive or disinterested.

Attentive care should be rewarded—leading to increased interactivity, new "skills," or subtle emotional cues that reinforce bonding.

Encouraging natural responsibility—rather than scripted demands, small behavioral shifts can nudge users to instinctively care for it (like making "hungry" sounds subtly instead of flashing a low-battery warning).

b) Familiarity and Individuality: Making It Feel Like "Your" Animal

For an emotional bond to develop, a robotic animal must not feel like a mass-produced clone.

Personalization is key—allowing users to name it, dress it up, or customize minor details.

Consistent memory of interactions—recognizing specific people and adjusting behavior accordingly (e.g., acting differently toward a frequent caretaker vs. a stranger).

Stable presence—unlike virtual pets that disappear when the app is closed, robotic animals should always be findable, summonable, and persistent in their relationships.

c) Communication: The Key to Emotional Depth

Real animals don't just follow commands—they express wants, preferences, and moods. A robotic animal should have:Ways to convey its state—subtle changes in movement, posture, or sounds to indicate emotions.

Two-way communication—users should be able to express care through touch, voice, or interaction, and the robot should respond accordingly.Expressive autonomy—at times, the robotic animal should initiate interactions, "choose" to seek attention, or exhibit curiosity, making it feel less like a reactive toy and more like a living presence.

5.3.2.3 Two-Way Interaction: Love, Frustration, and Everything In Between

For a robotic animal to truly feel real, it needs to experience and express emotions beyond just affection.

Positive reinforcement—snuggling, playfulness, or small "rewards" when treated kindly.

Reactions to negative interactions—if ignored or mistreated, it should show reluctance, avoidance, or hesitation (rather than blindly responding as if nothing happened).

Emotional variation—not all interactions should be predictable; the robotic animal should occasionally express moods that are unexpected yet logical (like being playful some days and more reserved on others).

Even frustration and misbehavior can add to believability. A robot that occasionally refuses to obey or "teases" the user adds a layer of depth—just like how real pets sometimes act stubborn.

Conclusion: More Than Just an Interactive Toy

The most compelling robotic animals won't just execute tasks—they will grow, change, and react based on experience. They should be capable of remembering individuals, developing unique behavioral quirks, and evolving in a way that makes companionship feel earned rather than pre-programmed.

A robotic animal is not just a machine that performs actions—it is a simulated life form that should feel personal, responsive, and emotionally significant. If done right, it will not only provide companionship but challenge and enrich human experiences, making people question: Is this really just a machine?

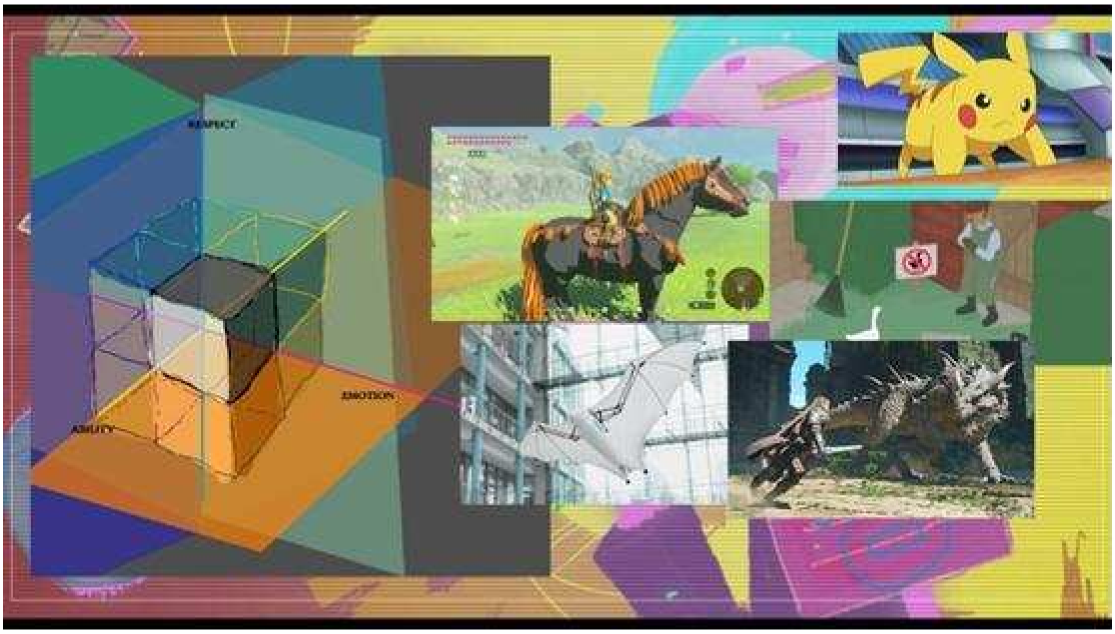

Figure 43 Virtual Animals have same system of relationship build

Unlike virtual animals, robotic animals exist in the real world, meaning their physicality immediately grants them an edge in the ability category—they can interact with the physical environment, respond to human touch, and occupy real space. However, just like virtual animals.

Pikachu (All Three Dimensions)

A near-perfect virtual companion. It loves its trainer, shows respect by responding independently, and has abilities that assist the player.

Festo’s Bat Robot (Respect, but Limited Love and Ability)

The robotic bat, much like real bats, earns respect due to its impressive bio-inspired flight, delicate mechanics, and ability to navigate autonomously. However, it is not designed to love or help humans—it does not interact in a way that builds companionship, nor does it serve a practical function like a service robot. If integrated into a social robotics framework, it would need more ways to express affection or purpose.

Zelda’s Giant Horse (Love, Respect, and Ability)

Like real horses, it has its own temperament (respect), can be tamed and bonded with (love), and serves as a powerful mode of transportation (ability). It behaves like a true companion, rather than just an interactive object.

Paro, the Therapeutic Seal (Love and Ability, Less Respect)

Unlike a robotic bat, Paro is explicitly designed for human bonding. It builds love through physical contact and emotional responses. It has ability in therapy, helping people cope with loneliness and stress. However, it lacks respect in the sense that it does not assert its own independence—its responses are highly predictable.

When I look at the different kinds of animals in The Sims 4, I can't help but see how they reflect real-life relationships with animals—and, more importantly, how these distinctions could apply to robot animals. The game divides animals into three main categories: pets, farm animals, and wild animals, and when you think about it, these categories aren't just about what the animal looks like or where it lives—they're about how much responsibility people feel toward them and how deeply they engage. The same logic can apply to robot animals. A household robotic pet would be like the in-game cats and dogs—always present, needing attention, forming close emotional bonds. If I designed a robot like that, it would have to make people feel needed— maybe by reacting when it's ignored, simulating health fluctuations to encourage caretaking, or offering clear affection in return for attention.

Then there are farm animals, which in The Sims aren't as personally attached but still rely on people to feed them, clean them, and make sure they thrive. The game even rewards good care by letting you enter contests for the best milk or eggs—there's a clear gamification of responsibility happening there. If robotic animals were designed in this way, they wouldn't necessarily need to produce real food (though imagine if they dispensed little vitamin-enriched "milk" packets?), but they could have some kind of virtual output—maybe digital products linked to an app, something that grows or changes based on how well they're cared for. And then there's the wild animals—The Sims lets them roam around, sometimes interacting with people, sometimes not. They don't belong to anyone, and they don't ask for much. That, to me, is a model for free-roaming robotic creatures in public spaces—ones that recognize people but don't "belong" to any single person, ones that react to their environment on their own terms rather than always seeking human approval. What I find fascinating is that our expectations of responsibility shape our relationships—if we think something is "ours," we take care of it differently than if it's a shared resource or a passing presence in our environment.

And if we're rewarded for taking care of something, we're even more invested. That's something robot animal design should take into account—whether through virtual incentives, social recognition, or real-world companionship mechanics. People don't just love animals because they exist; they love them because they grow, respond, and change in ways that feel meaningful. So maybe the question isn't just what robot animals should look like or act like, but what kind of responsibility and engagement system makes people feel connected to them in the first place.

Figure 44 Care cow in Sims4

Among all the expansions of The Sims 4, the Wild Animals DLC is particularly worth mentioning because it introduces a unique category of animals—foxes and rabbits—that exist outside the traditional concept of ownership. These animals have names, favorite objects, different appearances, and distinct personalities, yet they do not belong to anyone. Unlike household pets that require constant care, or farm animals that provide material benefits, these creatures simply exist in the world, interacting with humans on their own terms. The relationship between humans and these wild animals is built on accumulated positive interactions—feeding them, gifting them items, playing together—all of which gradually increase their favorability. A fox that was once a mischievous egg thief might, over time, stop stealing from the player's chicken coop, or even protect the chickens instead. Rabbits, if they form a bond with the player, might move closer to their home and become a friendly neighborhood presence—not quite a pet, but also not a stranger.

What makes this design so interesting is that it mirrors real-world animal behavior. Many animals, despite being untamed, recognize and develop relationships with humans based on repeated interactions. Some even offer gifts—although their choice of gifts may not always be appreciated. Cats, for example, often bring home "presents" in the form of dead bugs or small animals, much to their owner's horror. This kind of non-transactional interaction—where animals choose to give rather than being conditioned to do so—adds a layer of realism to the Sims 4 design.

For robotic animals, this concept offers a huge source of inspiration. It suggests that even public, non-owned robots—those that exist in shared spaces rather than as private companions—can still form individual relationships with people based on past interactions. Imagine a robotic animal in a public park that remembers frequent visitors, greeting those who have previously played with it more enthusiastically than strangers. If someone once helped it out—perhaps by clearing an obstacle in its path or guiding it when it was lost—it might become more cooperative with them in the future. These robots could even "offer gifts" in a similar way, either by physically retrieving and handing over objects (like a playful dog bringing back a stick) or by granting virtual rewards in an associated app.

But the most intriguing implication of this design is the potential for community-based protective mechanisms. In Sims 4, foxes that are treated well will stop stealing and may even protect a farm’s livestock. This principle could be extended to real-world robotic animals as well. If a robotic animal is designed to recognize and remember human behavior, it could also recall negative interactions—such as instances of aggression or mistreatment. Over time, such robots could subtly reflect their experiences in their behavior, avoiding or displaying wariness toward individuals who have previously been unkind to them. In a public space, this would create an interesting form of social feedback: if someone regularly bullies the robotic animal, others may start to notice the robot’s defensive or distrustful reactions, indirectly identifying the mistreatment. This could deter potential mistreatment simply because people do not want to be socially perceived as "the person who kicks the public robot."

This opens up a fascinating discussion on how robotic animals can encourage ethical human behavior without direct enforcement. By incorporating memory and social recognition, public robots could subtly guide interactions in a way that promotes kindness and accountability. It would be less about punishing wrongdoers directly and more about making mistreatment socially undesirable—because let’s be honest, no one wants to be the villain in a space where even a robot refuses to befriend them.

Figure 45 Wild Fox taking egg in Sims4

Figure 46 Wild rabbit live with human in Sims4

Despite the incredibly detailed and diverse human-animal interaction systems in *The Sims 4*, its design cannot be fully translated into real-world robotic animals due to two fundamental differences: time perception and first-person experience. In games, time often moves at an accelerated pace—players can witness an animal's entire lifecycle within just a few hours. This creates an unnatural and even detached experience for the player. I once raised a cat in *The*

Sims 4, and because of the game's time compression, every ten in-game minutes, it seemed to be getting sick, needing urgent vet visits. Meanwhile, my real-time interactions with it—playing, petting, bonding—remained at a human pace. The result? An overwhelming sense of detachment. A cat that lived for only three in-game days had fallen ill a hundred times, while I had only played with it ten times. Instead of forming an emotional bond, I felt exhaustion and indifference. This highlights a crucial aspect of real-world robotic animals: the importance of time synchronization with human perception. A robotic animal must build its relationship with a human over a natural, unhurried duration, reinforcing continuity and emotional depth rather than rushing through artificial milestones.

That being said, one feature from *The Sims 4*'s pet system holds strong potential for robotic animals—the training system. Players can train their pets in jumping, tunneling, and agility courses, and even enter competitions for rewards and recognition. This interactive element isn't just about skill progression; it creates a shared experience between human and animal, fostering a sense of collaboration, achievement, and pride.

For robotic animals, incorporating similar

cooperative training mechanisms—whether through obstacle courses, coordination-based tasks, or even problem-solving games—could significantly strengthen the emotional bond between user and machine.

However, when analyzing game-based animal interactions, we cannot solely rely on the "good human-animal relationship" model. Many games are not designed to simulate long-term companionship but instead focus on unique and specific interaction mechanics. Understanding these mechanics helps identify innovative design inspirations that can be selectively integrated into robotic animal behavior.

One exemplary case is Planet Zoo, which, although not centered around first-person interaction with animals, provides one of the most intricate and lifelike animal behavior systems in gaming. Animals in this game live independent lives—they play, eat, get sick, interact with their environment, and even escape their enclosures if conditions are inadequate. They respond to weather, exhibit stress in crowded areas, and require companionship with certain species to maintain well-being. What makes this so valuable for robotic animal design is not the specific in-game mechanics but the philosophy behind them—the richness of behavioral diversity. A robotic animal doesn't need to interact with a human at all times; sometimes, simply observing its independent activities can already create immersion. Planet Zoo demonstrates how well-crafted animations and behavioral logic can make an animal feel "alive" even when it is notexhibit independent behaviors when left alone, while shifting to more interactive behaviors when a human approaches. This creates the illusion of a dynamic, autonomous creature rather than a static programmed machine.

Another key takeaway from Planet Zoo is its deep consideration of animal welfare and environmental adaptation. Players learn that animals need more than just food and water; they require specific habitats, climate conditions, social groupings, and stimulation to thrive. For robotic animals, this suggests that their design should not only focus on technical functionality but also simulate contextual environmental preferences. A robotic mole, for instance, might "prefer" dimly lit spaces, while a robotic frog could be programmed to behave more actively in humid conditions. These conditions don't necessarily need to be real—a machine doesn't require actual water, but it could respond to a blue-colored surface as if it were a pond, "swimming" over it. Similarly, a robotic turtle might instinctively "bask" in direct sunlight by pausing and exhibiting slow, stretching movements. By designing robots that appear to have envispatial awareness, color recognition, or object interaction triggers—we not only make them feel more lifelike but also provide users with a more intuitive and immersive way to care for them.

Ultimately, while video games offer incredible reference points for robotic animal interaction, the key difference is time and persistence. In games, relationships are compressed into a matter of hours or days, often dictated by the player's level of engagement. In the real world, robotic animals must account forhuman attention spans, ensuring that interactions remain engaging over months or even years. They must **slow down, remember, adapt, and respond overslow down, remember, adapt, and respond over time, creating the gradual, evolving relationships that define true companionship.

Figure 47 *Planet zoo* raccon

This is a fascinating observation—proving that even with minimalistic graphics and simplified mechanics, a game like Let's Build a Zoo can still convey an incredibly rich understanding of animals, their needs, and the complexities of managing their well-being. Unlike Planet Zoo, which relies on detailed animations, 3D models, and deep AI behavioral systems, Let's Build a Zoo achieves nearly the same level of depth with a much simpler algorithm. It effectively incorporates elements such as rescuing and rehabilitating animals, selective breeding, technological progression, habitat and diet requirements, and even interspecies relationships—both cooperative and competitive. This suggests that highly complex mechanics and deep simulation aren't always necessary to create the feeling of a realistic and dynamic animal system. Instead, well-structured design and carefully chosen game rules can be just as effective in educating players about animal welfare and behavior.

This approach has direct implications for robotic animal design. One key takeaway is the potential for visual and behavioral variability through modular customization. For example, robotic animals could incorporate physical traits influenced by simulated genetic combinations, just as Let's Build a Zoo allows players to breed animals with unique features. This could manifest in customizable physical parts—such as different eye colors, fur textures, body shapes, or ear and tail designs—or through more digitally adaptive features like changeable display elements. A robotic animal with an integrated screen for eyes could subtly adjust pupil shape, brightness, or color to reflect individual differences. Alternatively, some robotic animals could produce unique "eggs" (a symbolic digital or physical token representing offspring), which users might collect, trade, or redeem for new robotic features—potentially even through real-world rewards like mailed components or store pick-ups.

Another crucial insight is *Let's Build a Zoo*'s use of multi-species interactions and social dynamics, which can also be applied to robotic animals. The game demonstrates how animals respond to population density (overcrowding leads to stress), species type (compatibility with others), and species diversity (single-species environments encourage intraspecies behaviors, while multi-species enclosures trigger interspecies interactions). These simple yet effective mechanics suggest an intuitive way to simulate animal-like preferences and relationships in robotic systems without requiring highly advanced perception or AI. Instead of needing precise environmental analysis, robotic animals could simply be programmed with basic behavioral triggers—detecting nearby robotic "species" through wireless communication, RFID tags, or simple proximity sensors—and responding accordingly. For example, if a robotic wolf detects too many of its own kind, it could express territorial behaviors; if it detects a different species, it could trigger cooperative or neutral interactions. This doesn't have to be scientifically accurate—after all, even real-life zookeepers take creative liberties when designing enclosures—but it does reinforce the idea that robotic animals, like real animals, have "preferences" and "needs," making them feel more alive.

Figure 48 *Let's build a zoo*

Zoos that focus purely on breeding capabilities or showcasing rare species—often at the cost of proper welfare—raise ethical concerns. These institutions sometimes prioritize the novelty and spectacle of exotic species over their actual well-being, housing animals in environments unsuitable for their natural behaviors. This is where simulated animals or artificial creatures

present a compelling alternative: rather than exploiting real animals for human curiosity, we can create any species we desire—whether it's a dinosaur, a unicorn, or even Cthulhu itself—without compromising welfare. Unlike real-world breeding programs, artificial creatures are not bound by biological constraints, making them a safe and ethical solution for those drawn to rare or fantasy species.

Several video games have explored alternative approaches to animal breeding and genetic experimentation, offering insights into how artificial life can satisfy human curiosity while avoiding harm to real animals. For example, *Husbandry* takes an unrestricted approach to multi-generational hybridization, allowing players to crossbreed rabbits, phoenixes, worms, and even humans, showcasing the endless genetic possibilities within a virtual system. Similarly, the game *Creatures* offers a sandbox for artificial evolution, where players design unique species with evolving traits and pit them against each other in a test of adaptability.

However, not all games take a purely experimental or speculative approach—some focus on ethical animal management and conservation efforts. *Planet Zoo* provides a serious zoo simulation experience, immersing players in the challenges of responsible zoo operation. Unlike games that encourage unrestricted breeding or experimentation, *Planet Zoo* emphasizes animal welfare, habitat design, and species conservation. It features a sophisticated welfare evaluation system, requiring players to create optimal environments with natural vegetation, appropriate social structures, and multi-species symbiosis. Over time, players unlock toys, enrichment tools, and better living conditions, encouraging them to view zoos not just as spectacles, but as spaces where animals can thrive.

At the same time, *Planet Zoo* also reflects the reality that humans often test the limits of their control over animals, with many players engaging in pranks or even cruel treatment—throwing animals, ignoring their needs, or deliberately causing chaotic conditions. While this may seem unethical, games provide a safe outlet for such behaviors, allowing people to explore power dynamics without real-world consequences. This could serve as an alternative solution for satisfying darker human impulses—offering artificial lifeforms that react, resist, or respond dynamically to mistreatment, without actual suffering. If machine animals or artificial creatures are designed with similar principles, they could channel people's curiosity and sometimes destructive tendencies into ethical and engaging interactions, reducing harm to real animals while still providing meaningful experiences.

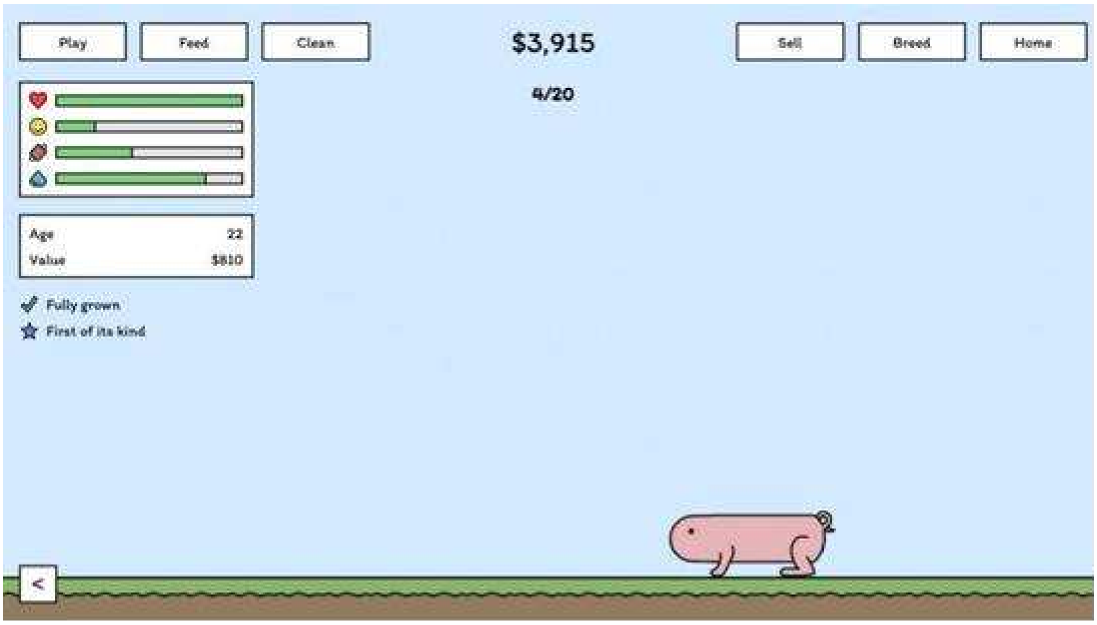

Figure 49 Pig and rabbit and worm mixed in Husbandry

At the same time, during a discussion with Anne about whether simulating hunting, live animal experimentation, or even animal mistreatment in games could serve as an outlet to divert people's desire for control over animals, she raised an important counterpoint: rather than reducing harmful behaviors, such games might actually increase the likelihood of real-world animal abuse. Research in psychology suggests that violent or cruel interactions in virtual environments can sometimes reinforce negative behaviors rather than providing a safe catharsis (Anderson & Dill, 2000). Instead of curbing destructive tendencies, such simulations might desensitize players to suffering, making them more likely to repeat similar actions in reality (Gentile et al., 2009).

This underscores an important ethical consideration in game design: while giving players freedom to interact with virtual animals is essential, the mechanics should still guide players toward positive interactions and constructive relationships. Encouraging people to treat animals with respect—whether real or virtual—helps reinforce the idea that animals are not merely objects for human amusement or power trips, but beings (real or artificial) that deserve ethical consideration.

This aligns with the design philosophy for robotic animals as well. If machine animals are meant to simulate real-life companionship, their behavior and responses should encourage ethical and meaningful human-animal relationships, rather than normalizing neglect or abuse. Negative reinforcement—such as programmed distress signals or avoiding mistreatment-prone individuals—could help deter harmful interactions. Additionally, introducing positive reinforcement mechanisms, like rewarding users for gentle interactions, responsible caretaking, or cooperative activities, would reinforce pro-social behaviors and deepen users' emotional investment in robotic animals.

Ultimately, while games and robotic animals offer simulated experiences that can model human-animal relationships, they should do so with carefully considered ethical constraints, ensuring that they promote empathy, responsibility, and respect rather than reinforcing the power imbalance and harm that has historically definpower imbalance and harm that has historically defined many human-animal interactions.

This next example introduces a game that focuses on animal behavior and collection, demonstrating how simple mechanics can create a deeply immersive experience with virtual animals. The game itself is not complex, yet it beautifully captures the lively and adorable movements of dogs in various settings. As the player walks through the environment, they naturally become drawn to the diversity of dogs, each engaging in different activities. These dogs do not possess highly intricate behavioral systems; instead, they are programmed to perform a limited set of specific actions around certain objects. However, because of their varied animations and naturalistic placement, the scene feels dynamic and alive. One particularly effective design choice is that the dogs react when players approach them, making eye contact or adjusting their posture, which strengthens the illusion of real interaction. Beyond this, the collection mechanic plays a significant role in fostering emotional engagement. By taking photos of different dogs, players unlock achievements, and their growing collection symbolizes a deepening bond with these virtual creatures. This mechanism of discovery and recognition can inspire the design of exhibition-style robotic animals, where the primary goal is to immerse visitors in a world populated by believable animal-like machines, even if these machines do not possess advanced cognition or real-world sensory capabilities. From a robotics design perspective, this approach suggests that large-scale interactive robotic animal installations do not need complex AI or real-time adaptive behavior. Instead, the focus should be on simple, pre-scripted reactions tied to visitor presence, such as looking up, blinking, staring curiously, backing away, or playfully approaching. These limited behaviors, when strategically assigned to different robots across an environment, can collectively create a rich, engaging experience without the need for deep learning algorithms or complex autonomy. To further enhance visitor engagement, additional elements can be introduced, such as robot-to-robot interactions, where even if the robots do not perceive each other in real-time, pre-set animations of play-fighting, chasing, or sniffing can make them seem more socially aware; exploration-based rewards that encourage visitors to seek out and observe different robotic animals through an achievement or collection system, creating a sense of progression; and environmental triggers where robots respond to specific elements in their surroundings, such as moving toward designated "play areas" or "sunbathing spots," reinforcing contextual believability. This kind of passive yet interactive system offers a scalable, cost-effective approach to large-scale robotic animal installations, making them ideal for zoos, theme parks, or museums where the goal is to immerse visitors in an engaging, animal-like world without the burden of real-time complex computation.

Figure 50 Pupperazzi

Figure 51 Collection system in Pupperazzi

The game *Dave the Diver* provides an astonishingly accurate simulation of fish behavior, not just at the individual level but also in large-scale group dynamics. It meticulously replicates schooling behaviors, predatory responses, and defensive mechanisms, making the ocean feel incredibly alive. Each species has its own unique movement pattern and reaction to external stimuli. For instance, some fish react aggressively when approached—tiger sharks charge head-on, eels dart out from their hiding spots to bite, stingrays bury themselves in the sand and ambush, crabs leap up to pinch, hammerhead sharks swing their heads wildly to attack, squids release ink to obscure vision, and tuna, with their powerful speed, can knock the player back with sheer force. These diverse behaviors make the game feel more like an immersive exploration of marine life rather than a mere fishing simulation. Even without the goal of earning game points, players are naturally drawn to the joy of watching, interacting with, and navigating through the living ocean world. The most significant interactive behavior in this game is "attack", a rare design choice for animal-focused interactions. While the goal of robotic animals is primarily peaceful companionship and cooperation, the incorporation of dynamic, challenge-based interactions inspired by aggressive animal behaviors could significantly enhance the sense of realism and engagement. Instead of actual hostility, robotic animals could feature playful challenges that mimic natural confrontations—such as dodging, resisting, or engaging in tug-of-war behaviors—providing an experience that feels more organic and lifelike.

Figure 52 Dave fight with big fish in Dave the Diver

Additionally, Dave the Diver introduces a mini-game called GYAO, where players raise aquatic creatures by feeding, training, and caring for them. The mechanics encourage nurturing behavior through curiosity about the unknown and the responsibility of preventing accidental pet deaths. If adapted to robotic animals, this concept could take the form of adaptive growth and behavior development based on user interaction patterns. Rather than starting with a predetermined species, robotic animals could begin with a generalized, ambiguous form and evolve their behaviors, sounds, and responses based on how they are cared for. For example, a robotic animal could develop distinct "species-like" characteristics over time—such as ears that either droop or stand upright to signal different evolutionary paths, or movement styles that shift from hopping to walking to crawling based on user engagement. This would not only deepen user attachment by making each robotic animal uniquely tailored to its owner’s personality and habits but would also create a progressive interaction loop, where users are encouraged to shape their companion’s identity through consistent engagement. If implemented effectively, this approach could result in robotic animals that feel more dynamic and customizable while reinforcing meaningful and personalized human-animal bonds.

Figure 53 GYAO game have shark as result

The game *Animal Shelter* provides a compelling simulation of caring for rescued animals, emphasizing the responsibilities involved in temporary animal welfare. The game mechanics include a rich variety of caretaking interactions, such as bathing (detailing every step from brushing, shampoo application, scrubbing, and rinsing), feeding (purchasing food and scheduling meals based on needs), playing (throwing and retrieving balls, petting, using laser pointers to encourage movement), and finding suitable adopters for the animals. In a first-person 3D environment, these actions feel surprisingly realistic—perhaps even tedious and repetitive at times—which is arguably reflective of the real-life experience of working in an animal shelter. The game conveys the weight of responsibility that comes with caring for multiple animals, rather than just a single cherished pet.

However, from the perspective of robotic animal design, the lack of long-term bonding in the game presents a notable limitation. The game focuses on short-term interactions with a revolving roster of animals rather than fostering long-term emotional connections or allowing players to witness the growth and development of a single companion. While this suits players who enjoy novelty or those motivated by a sense of mission-driven animal rescue, it does not replicate the deeper companionship that many seek in pet ownership.

The care-oriented mechanics in *Animal Shelter* can be meaningfully adapted to robotic animals, incorporating interactive elements that simulate care behaviors without requiring actual biological needs. For example, users could "bathe" robotic animals using props or blue light projections instead of real water, feed them using specialized objects or a paired digital interface, pet and physically interact with them, and even help maintain their "health." The latter could be particularly compelling if robotic animals display distress or malfunction states that require user intervention—either as scripted behaviors that mimic biological illness or as real technical issues that need to be addressed, such as low battery levels, accidental falls, sensor malfunctions, overheating, or mechanical failures. In this way, users would not only experience the fulfillment of "saving" an animal in need but also engage with a practical and rewarding caretaking process that enhances their sense of responsibility. This aligns well with the psychological gratification of caregiving, transforming even maintenance-related tasks into emotionally meaningful interactions rather than mere technical troubleshooting.

Figure 54 wash dog in *Animal Shelter*

5.3.3 Presets and Storylines: Theatricality in Robotic Animal Design

In an interactive narrative game, characters don't need real intelligence to give players a strong sense of interaction—they just need well-crafted plot structures and expected branching options. Players feel engaged because the narrative adapts to their actions, even though the game simply follows pre-programmed paths. This principle applies to robotic animals as well. If we can't give them real-world intelligence capable of handling unlimited complexity, we can instead design them like performers in an interactive drama—pre-programming engaging storylines and letting people influence outcomes at key decision points.

This concept mirrors live-action interactive theater, where audiences interact with actors and shape the unfolding story. The only difference is that instead of actors, we use robotic animals to play the role of "interactive animal companions." The beauty of this approach is that people already have lower expectations for animals—in reality, animals don't always react predictably, nor do they always respond in ways that humans fully understand. This natural "tolerance" for unpredictable animal behavior works in favor of robotic animals, as even minor correlations between human interaction and robotic response will feel meaningful to users.

Moreover, this method can mask technological limitations. Since real animals don't always behave predictably, robotic animals don't need to give precise, logical, or even consistent responses all the time. Instead, their reactions can be wrapped in a layer of theatrical ambiguity—a "mist of animal unpredictability"—that allows users to project their own interpretations onto interactions. A robotic animal that sometimes tilts its head at a person, sometimes ignores them, and sometimes "mysteriously walks away" can be perceived as having personality rather than being flawed.

In this way, robotic animals don't have to be highly advanced AI to create meaningful interactions—they just need well-designed narratives, dramatic tension, and the illusion of autonomy. Whether through pre-scripted behaviors triggered by user input or subtle randomness that makes responses feel organic, we can create believable, engaging robotic animal experiences that feel real without requiring true cognitive sophistication.

Chapter 6 Practice-Development of GUA

This chapter is the most personal. It shows how GUA was made—not just technically, but emotionally. Each version was built with hands and guesses, through problems I didn't know how to solve until I touched them.

Some of the robots worked. Some didn't. Some just sat there looking confused. But each one taught me a little more about how machines move, how softness changes meaning, and how building something over and over is a kind of companionship, too.

6.1 GUA 1.0

6.1.1 How GUA was designed

6.1.1.1 Inspiration: From Guagua to Robotic Companionship

I once rescued a baby gray magpie and named him Guagua. He was full of personality—curious, mischievous, and expressive. He would stretch out his long neck to play, disrupt my drawings by hopping onto my sketches, and react uniquely to different people and objects. He wasn't just a passive pet—he had preferences, ambitions, and a clear sense of agency. Raising him and eventually releasing him back into nature made me realize how rich and unpredictable real animal behavior is. It also made me wonder—could a robot ever feel this alive?

That's when I decided to build a robotic companion that wasn't just a set of mechanical movements, but something that could sense the world, develop a relationship with people, and respond in ways that felt as natural as Guagua did. Not just a machine that obeys commands, but a presence—something you'd want to interact with, not just control.

The Problem with a Bird-Shaped Robot

At first, I tried to replicate Guagua directly, designing a robotic bird with jointed legs, a moving beak, and artificial wings. But it quickly became clear that birds move in ways that are fundamentally different from robotic arms. Their balance, wing coordination, and lightweight skeletal structure were impossible to mimic with rigid, motor-driven joints. Instead of a lively, expressive creature, I ended up with something stiff and unnatural—like a taxidermy bird suddenly animated by motors.

Adding a soft skin to cover the robot only made things worse. The material got caught in the moving joints, restricted motion, and revealed the hard metal structure underneath whenever it shifted. Instead of feeling like a warm, living creature, it looked like a fragile, uncanny puppet—neither convincingly biological nor purely mechanical. It wasn’t comforting. It wasn’t natural. And worst of all, it wasn’t fun to interact with.

A New Approach: Modular, Flexible, and Animal-Like

This forced me to rethink the design entirely. Instead of rigidly copying a bird, I asked myself: What made Guagua feel real? Was it his wings and beak? Or was it his fluid movements, his soft texture, his unpredictable reactions?

That’s when I started experimenting with a segmented, modular design—one that could move freely without rigid skeletal constraints, could have a soft, plush-like exterior, and yet still exhibited clear animalistic behaviors. It no longer had to be a bird. Instead, it could be a new kind of creature, borrowing movement patterns and interactive behaviors from a range of animals rather than mimicking just one.

This shift in thinking opened up entirely new possibilities—ones that were not limited by mechanical constraints but instead worked with them. The goal wasn’t to create a perfect replica of a real animal. It was to capture the essence of companionship and presence—something that could move, react, and engage in ways that felt right, even if they weren’t tied to a specific species.

Figure 55 My bird GUAGUA

6.1.2 How We Built It: The Structure and Intelligence of Gua

Gua's skeleton is built from seven servo combinations, giving it a flexible, elongated body capable of expressing emotions through movement—whether bending forward, shaking its head, or lying down in an exaggerated lazy sprawl. Soft cotton fabric forms its outer layer, offering a plush, touchable texture, while composite fabric materials create a unique fur pattern.

Figure 56 GUA looking sketch

The core of Gua's behavior is a "three-dimensional animal state model", an independently developed system. This model processes sensor inputs—including light, gestures, sound, and ultrasound—to interpret environmental and human interactions. Based on this data, it classifies Gua's emotional state, determining its reactions before sending motion commands to its servo driven body via Arduino. The result? Gua sees, hears, and reacts, creating the illusion of a sentient robotic creature.

Figure 57 One of the GUA looking

6.1.3 Challenges We Ran Into: Explosions, Stuck Joints, and Fabric Nightmares

Building Gua was not easy. Technically and physically, it fought back:

1) The battery was unreliable, frequently running out of charge, and at one point, a charging failure triggered an explosion—shutting down power in the entire room.

2) The voltage alarm buzzer wouldn't stop ringing, haunting our work sessions like a robotic banshee.

3) The head mechanism—originally inspired by a hand-shaped structure—kept getting jammed, particularly the thumb joint. After countless failures, we decided to rip it off entirely.

4) Sensor fusion issues: Initially, we tried using a complex combination of sound, light, temperature, humidity, and gravity sensors to interpret Gua's environment. But correlating animal behavior with raw sensor data proved impossible. Eventually, we settled on a three-dimensional model of "emotion, activity, and cognition", which improved behavior interpretation.

5) Sewing struggles: Transforming fabric into a "lifelike" texture while maintaining mobility was brutal. The process resulted in injured fingers, tangled stitches, and occasional existential crises.

6.1.4 Accomplishments We're Proud Of

Despite the chaos, Gua emerged as a charismatic, unpredictable, and strangely rebellious creature—one that looked like it was about to bolt at any second. The most exciting achievements include:

The Three-Dimensional Animal State Model

Gua's behavior is calculated based on three key factors:

Emotion: Happy or distressed?

Activity Level: Active or lethargic?

Cognitive Engagement: Unconscious reaction or thoughtful response?

This model allows dynamic behavior generation instead of rigid, pre-programmed responses.

A Versatile Sensing System

Gua doesn’t just "detect humans"—it distinguishes between individuals and adapts its behavior accordingly.

It reacts to gestures, light levels, sound cues, distance, and movement, making interactions unique to each person.

Alone, it manages itself, mimicking independent animal behaviors.

Behavioral Authenticity from Real Animals

Gua's movements were inspired by extensive observations of mantises, dinosaurs, emus, and cats.

It can express excitement, curiosity, annoyance, and even mischief—sometimes cuddling up, other times delivering a dramatic "rejection" gesture.

Over tens of thousands of tests, we refined movement angles, speed, and timing across six joints to create fluid, expressive behavior.

A Wildly Unique Appearance

Designed by a team of mad artists, Gua’s "fur" is a patchwork of over 40 different fabrics, giving it a distinct, wasteland-chic aesthetic.

6.1.5 What We Learned

Building Gua was an intense mix of engineering, art, and improvisation. Key takeaways:

1) Teamwork: The ability to tolerate each other’s questionable snack choices.

2) LeapMotion integration: Exploring gesture-based interactions.

3) Animal behavior studies: Essential for designing realistic movements.

4) Arduino & sensor applications: Learning to fine-tune sensor data processing.

5) Robot design & development: Balancing mechanics and personality.

6) Sewing & plush crafting: Stabbing ourselves with needles, repeatedly.

7) Algorithm development: Turning raw data into lifelike responses.

8) Combat skills: Learning how to avoid Gua's sudden attacks.

6.1.6 What's Next for Gua?

Gua is evolving, and here's what's coming next:

1) "Living its best life"

a) Making friends, developing wisdom, and consuming more ethically sourced garbage.

2) Fashion experiments

a) Trying out new hairstyles, fur patterns, and bizarre accessories.

3) World travel

a) Visiting waste dumps in different countries (prime habitat)

b) Attending exhibitions & talks to share its philosophy of life.

1) The "AI Takeover" Upgrade

a) Transitioning from "lazy programmer's pet" to "robotic president with silver muscles".

b) Increasing social status dramatically.

2) Extreme environments

a) Exploring deep space or deep sea—where social introverts might need a companion most.

3) Cybernetic Enhancements

a) Installing wings, unicorn horns, mermaid tails, and laser eyes.

b) Connecting WiFi/Bluetooth modules for mobile app communication.

c) Using step count, location, weather, and gyroscope data to personalize Gua's behavior.

4) Expanding its education

a) Martial arts (so it can counterattack better)

b) Yoga (for more flexible movement patterns)

c) Pixar animations (for richer expressiveness)

d) Romantic turkey courtship displays (for dramatic flair)

e) Ancient puppet performances (for movement inspiration)

Gua isn't just a robot—it's an evolving entity. The goal isn't just building a machine; it's about creating something that feels alive, unpredictable, and truly its own creature.

Figure 58 GUA1.0

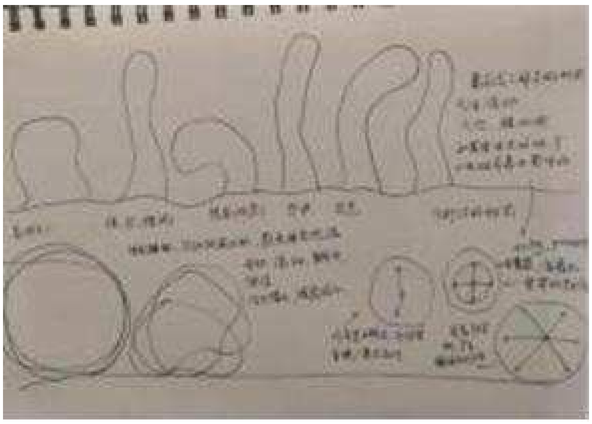

Figure 59 Sketch of actions

6.1.7 The Case for Non-Specific, Monster-Like Robotic Animals

When interacting with artificial creatures, labeling them as exact species can initially create a sense of familiarity. People instinctively relate to known animals, making the robot feel more approachable. However, this species-based identification is often shallow and short-lived—a quick mental shortcut rather than a deep emotional connection.

In real relationships, whether with animals or even with humans, familiarity transcends species classification. We stop thinking about someone as "a dog" or "a cat" and start seeing them as a unique individual, usually reinforced through naming and shared experience. Even among

purebred animals with nearly identical appearances, their personality and history make them distinct. This natural shift in perception suggests that focusing too much on species accuracy in robotic animals may be counterproductive—instead of enhancing engagement, it could create unrealistic expectations and inevitable disappointment when the simulation inevitably falls short.

Since current robotic animal technology cannot yet perfectly replicate real animal behavior, movement, or appearance, a new design strategy is needed. If we cannot meet the high expectations that come with attempting a "realistic" dog or horse, then why not embrace the ambiguity? If people’s expectations are deliberately adjusted, if the robotic animal is designed without a strict species identity, then the evaluation criteria shift—instead of being judged as a poor imitation of a dog, it becomes an engaging, organic creature in its own right. This roundabout approach may result in a more satisfying and flexible user experience.

6.1.7.1 The Limitation of Species-Specific Designs

A specific species comes with predefined expectations. No matter how many age variations, fur patterns, or size options we introduce, a dog is always a dog, a chicken is always a chicken. This restricts the range of behaviors and appearances that can be accepted—if a robotic horse doesn’t move exactly like a real horse, it risks being labeled as "incorrect" rather than being appreciated for what it can do. The problem gets worse when people mentally categorize these artificial animals based on real-world functions:

Working animals (e.g., cows, racehorses) are judged by their ability to perform labor.

Food animals (e.g., pigs, chickens) may feel "pointless" if they do not fulfill their biological role.

Culturally disfavored animals (e.g., donkeys in some contexts, rats, wild boars) can carry prejudices that impact the interaction.

Dangerous animals (e.g., tigers, venomous snakes) create an expectation of risk, making friendly interactions feel unnatural or forced.

In contrast, "monster-like" artificial animals—creatures without a clear species identity—avoid these biases entirely. They remove cultural baggage, avoid preconceived roles, and create an opportunity for people to engage freely, without expectations or subconscious judgments interfering.

6.1.7.2 Monsters as a Design Philosophy

By starting from an undefined "fictional species", robotic animals can bypass the need to fit into rigid biological frameworks. Instead of worrying about whether a robot dog wags its tail properly, we can focus on expressiveness, interaction depth, and emotional engagement. A monster-like robot isn't judged by realistic gait, diet, or sleep cycle, but by how it feels to interact with.

A robotic dragon, for example, does not need to adhere to any real reptilian behavior—it can stretch, hover, chirp, or blink its huge expressive eyes in ways that are engaging but free from scrutiny.

A fur-covered, long-necked creature might seem alien yet inviting, allowing people to project their own emotions onto it rather than comparing it to a known species.

A plush-like, round-bodied "creature" could exist simply for comfort and interaction, without the constraints of real-world zoology.

By embracing the absurd, the undefined, and the unfamiliar, robotic animals gain creative freedom. They no longer exist to mimic real-world species, but instead to provide an experience—one that is engaging, unpredictable, and free from expectation.

6.1.8 Why Fur? The Role of Hair in Robotic Animal Design

The biggest visual and tactile differences between humans and animals are "hair", and the biggest difference between machines and living creatures is "softness". Thick fur not only provides a plush, organic appearance but also offers a layer of softness that masks the rigid mechanical structure underneath.

But not just any fur—tattered, layered, and disordered long fur plays a crucial role. Unlike tightly fitted synthetic skin, which can reveal mechanical inconsistencies, long and uneven fur creates an illusion of organic randomness, making slight mechanical imperfections and distortions less noticeable. If the coat were made from a solid-colored, clean-cut material, any misalignment with the mechanical body would be immediately obvious, breaking the illusion of life. Instead, a chaotic, naturally layered fur pattern absorbs these small shifts, helping the robot maintain its lifelike movement.

Beyond aesthetics, fur also acts as a protective layer. It softens the impact of mechanical motion, prevents direct contact between metal joints and external objects, and in some cases, reduces noise by dampening vibrations. When a robotic animal moves, its synthetic fur subtly shifts with motion, further enhancing its organic presence.

Figure 60 Fur with recycle clothes

6.1.8.1 Segmented Fur Design: Flexibility & Maintenance

The mechanical body of GUA consists of six articulated segments (head claws, neck, shoulders, upper torso, lower torso, base), allowing it to move with six degrees of freedom. To maintain this flexibility while covering it with fur, I designed a segmented plush suit that consists of four main body sections + one headpiece.

Each plush coat section is independently removable, fastened around its mechanical segment using flexible pins. This modular approach makes maintenance extremely efficient—if one servo malfunctions, I can simply remove that section of the coat without dismantling the entire body.

Another challenge was preventing loose fur from getting caught in mechanical joints. To address this, each fur layer includes a protective inner lining, which tucks under the preceding layer when worn. This overlapping structure ensures smooth movement while keeping the mechanical core fully shielded from loose fibers.

Figure 61 Inner muscles

Material Innovations: Creating a "Soft Composite Structure"

A typical fur-fabric material is often too thin, failing to conceal the rigid angles of the mechanical skeleton beneath. Instead, I developed a multi-layer composite structure:

1) Inner Muscular Layer (Leather Bag Muscle)

a) The base layer is made from a thick bougainvillea-textured fabric, mimicking the firm but flexible nature of biological muscles.

b) This adds volume and density, ensuring the coat doesn't just sit flat against the robot's rigid body.

c) It provides attachment points for additional fur layers while keeping the mechanical body well-cushioned and structured.

2) Outer Fur Layer (Long Hair with Multi-Layer Strips)

a) Unlike commercial fur-covered robots that use a single-layer fabric, I opted for hand-sewn, individually stitched fur strands.

b) This method enhances visual texture, ensuring the coat moves independently from the machine's rigid body rather than simply stretching over it.

c) The layered approach blurs sharp mechanical edges, preventing the "hard surface under soft skin" effect commonly seen in synthetic animal designs.

3) Weird Inner Skin Color: Bright Red as a Functional Indicator

a) The inner surface of the plush suit is bright red—not for aesthetics, but for practical maintenance reasons.

b) When sewing the coat, the red base serves as a visual guide, ensuring all mechanical parts are fully covered.

c) When GUA moves, if excessive red is exposed, it signals a misalignment or a movement error, allowing for immediate adjustments before fur gets caught in joints.

The Advantage of a Soft & Fragmented Exterior

Most robotic animals today still use solid, molded synthetic skins, which limit movement and make maintenance difficult. In contrast, a segmented fur-based exterior offers several advantages:

1) Improves Mechanical Durability: Protects joints from dust, impact, and external interference.

2) Enhances Lifelike Movement: Instead of rigid mechanical motions, the layered coat adds natural shifting and flow.

3) Facilitates Easy Repairs: Individual segments can be removed and replaced, reducing downtime.

4) Masks Mechanical Artifacts: Any slight misalignment in servos or frame structure disappears into the organic randomness of the coat.

By embracing the imperfections of real fur, robotic animals can achieve a more convincing, resilient, and emotionally engaging presence, making them feel less like machines and more like creatures.

6.1.9 Segmented Structure & Modular Fur Design for GUA

The mechanical structure of GUA consists of six articulated segments: head claws, neck, shoulders, upper torso, lower torso, and base. Each of these segments has six degrees of freedom (5 servos with 180-degree joints + 1 rotating base with 360-degree motion). Given thissingle-piece plush suit would not only restrict movement but also create visible tension points where the fur doesn't move naturally with the structure.

To solve this, I developed a 4+1 segmented plush coat—four main body sections plus a separate headpiece. Each section is mechanically attached via flexible pins, allowing for independent removal and replacement of specific fur sections. This design makes maintenance significantly easier—if a servo malfunctions, I can remove and replace the corresponding coat section without dismantling the entire body.

Additionally, robotic movement introduces a major risk—the possibility of fur getting caught in mechanical joints. To prevent this, I added a thin protective inner lining to the lower edge of each fur section. When assembling the suit, each layer overlaps the next like armor plates, ensuring that even with movement, there is no exposed mechanical structure where fur could get pulled into gears.

Layered Fur & Composite Materials for a Softer, More Organic Appearance

Leather Bag Muscle + Hair (Soft Composite Structure) A long-haired, layered fur coat is not just for aesthetics—it plays a critical role in masking mechanical imperfections and maintaining an organic look. Through trial and error, I identified three key material design principles

The base layer of the plush suit is not just fur, but a sculpted composite material resembling muscle texture. I achieved this effect by sewing the base layer from bougainvillea-textured fabric, which adds thickness and elasticity, creating a natural “plush” look while also allowing for proper attachment of fur layers.

Most commercial robotic animals use a single-layer synthetic fur fabric, which presents several major issues:

1) It is too thin, making the sharp mechanical angles beneath clearly visible.
2) It lacks structural volume, causing it to lie flat and lifeless over the rigid frame.
3) It is prone to shifting and slipping, especially in areas with frequent movement.

By using layered fabrics with different densities, I was able to better conceal mechanical parts while maintaining a natural, flexible shape. This design is particularly useful for robotic animals that need to maintain a realistic appearance in dynamic movements.

2. Fragmented Fur Coat for Modular Maintenance

Unlike synthetic skins used in commercial animatronics (which require full removal for internal access), GUA's coat is designed with segmented detachable fur layers. Each fur section is individually secured around mechanical joints, making repair and customization far easier.

3. “Weird Skin Color” as a Functional Indicator

The inner surface of the plush suit is bright red—a decision that is both practical and symbolic:

1) Maintenance Guide: When sewing fur, the red inner layer serves as a visual reminder to ensure complete coverage.
2) Movement & Wear Detection: If excessive red is exposed, it signals misalignment or movement errors, allowing for immediate adjustments.
3) Preventing Fur Damage: This helps avoid situations where fur gets pulled into servos, which can lead to mechanical failure.

6.1.10 The Evolution of GUA's Three-Dimensional Behavior Model

GUA 1.0 was the first iteration where I introduced the "three-dimensional animal behavior system", which defines robotic animal behavior using three primary variables:

1) Activity Level (Physical Motion & Responsiveness)

2) Autonomy (Decision-Making & Goal-Oriented Behavior)
3) Mood (Emotional State & Social Interaction)

This system evolved through multiple iterations, with GUA 3.0 still incorporating refined versions of the same core principles. The flexibility of this model means it can be scaled in complexity depending on available sensor input and computational power.

By adjusting the number of sensors, processing capability, and interaction rules, this model remains adaptable—whether used for simple, low-power robots or advanced AI-driven robotic animals. Despitcore idea of simulating organic, unpredictable animal behavior remains fundamental to the future of robotic animal development.

6.2 Robot Dog

6.2.1 Why dog

After the relative success of the GUA project, I was filled with a newfound confidence—perhaps too much of it. This sudden enthusiasm pushed me to take a much bigger leap toward creating a "real animal", and I set my sights directly on designing a robotic dog. I even managed to build an early interactive model, complete with a functional four-legged robotic structure and initial movement mechanics.

However, this process quickly revealed a major flaw in my approach. While quadrupled mobility undeniably improved movement capability, it came at the cost of flexibility and expressive behavior. Animal-like expressiveness—especially the subtle, nuanced behaviors that make animals feel alive—became much harder to replicate. The more mechanical complexity I introduced, the more rigid and artificial the robot's actions became.

Additionally, with every added joint, sensor, and computational element, the control system became exponentially more complex—to the point where it was nearly impossible for a small research team to fully realize. This wasn't necessarily a failure, but rather an important realization:

6.2.2 Why not dog

For socially-oriented robotic animals, more complexity isn't always better. The most effective designs aren't the ones that mimic real animals with painstaking accuracy, but the ones that strike a balance between simplicity, usability, and lifelike behavior.

This shift in design philosophy has several advantages:

1) It lowers unrealistic expectations. When people see a robotic dog, they expect dog-level intelligence. But no current robotics technology can match the cognitive abilities of a real mammal. By moving away from direct species mimicry, we free the design from impossible comparisons.
2) It encourages curiosity and open-ended interaction. If people aren't bound by preconceived notions of a species' behavior, they are more likely to approach the robotic animal as something new, learning its personality and forming a unique bond rather than judging it against a real-world counterpart.
3) It allows for better optimization. Certain biological structures (e.g., complex quadrupedal gaits) aren't ideal for robotic systems. By designing for function rather than strict biological accuracy, we can create better movement efficiency, lower energy consumption, and easier control mechanisms.

Ultimately, this experiment was not a failure, but an important turning point. The machine dog project taught me that realism isn't the goal—believability is. Designing robotic animals is not about perfect simulation, but about crafting a lifeform that feels natural, expressive, and engaging to interact with, regardless of whether it looks like a dog, a dragon, or a creature that doesn't exist anywhere else.

Figure 62 Robot dog sketch

Figure 63 Robot behaviour interaction design

Figure 64 Robot dog making

6.3 GUA2.0

6.3.1 Enhance Animal attributes

6.3.1.1 The Balance Between Realism and Abstraction in Robotic Animal Design

When we design robotic animals, a fundamental question arises: to what extent should they mimic real animals, and where should they diverge? While real animals provide an intuitive reference, blindly pursuing complete realism is often impractical and even counterproductive.

Instead, striking a balance between recognizable animal traits and practical robotic design is key to creating robotic animals that are both engaging and functional.

6.3.1.2 Why Avoid Humanoid Features in Robotic Animals?

One of the defining aspects of animals is that they are not human, and this distinction is central to why people enjoy interacting with them. Humans seek animal companionship not because animals are miniature versions of themselves but because animals offer a unique perspective, distinct behavior patterns, and a refreshing divergence from human social expectations.

However, when designing robotic animals, there is a temptation to anthropomorphize them—giving them expressive human-like eyes, speech capabilities, and exaggerated facial expressions. This is a common approach in entertainment media (such as Disney animations or Furby), but for a robotic animal meant to exist in the real world, excessive anthropomorphism can lead to an uncanny valley effect, making interactions feel artificial rather than natural.

To ensure robotic animals maintain a distinct, believable identity, several human features should be consciously avoided or minimized:

1) Facial Structure: Most mammals have smooth transitions between their snout and forehead, whereas humans have distinct facial planes with a prominent forehead. Keeping a smoother, animal-like structure helps distinguish them from humanoid robots.

2) Fixed Eye Placement: Human eyes are positioned on a flat, forward-facing plane, optimized for facial expression. Many animals, however, have lateral or recessed eyes, which can make interactions more organic when replicated in robotic designs.

3) Bipedal Walking and Arm Gestures: Giving a robotic animal upright posture and human-like gestures can unintentionally blur the line between "animal companion" and "social humanoid robot."

4) Speech: While vocalization is an essential interaction tool, robotic animals should rely on non-verbal sounds, tone variations, and movement rather than direct human speech to enhance believability.

6.3.2 Case Studies in Robotic Animal Design

Different robotic animals have approached the balance between realism and abstraction in unique ways. By analyzing both successes and failures, we can refine design principles for future robotic companions.

Keepon: Simple Yet Effective

Keepon is an excellent example of how a robotic animal can succeed with minimalistic design.

Despite its lack of fur, limbs, or complex animations, Keepon achieves meaningful interaction

through its ability to move and respond to human presence. Its simple rubber body provides a tactile experience, and its direct, intuitive responses make it an appealing companion. Keepon's success demonstrates that realism is not always necessary—sometimes, a simple, well-executed interaction model can be more compelling than complex features that are difficult to control.

PARO: The High-Cost Barrier

PARO, the robotic therapy seal, is another notable case. While PARO is undeniably cute and highly interactive, its high cost and relatively simple functionality limit its widespread adoption. The biggest drawback of PARO is that its price does not directly translate into a proportional improvement in interactivity. Unlike Keepon, which relies on movement and responsiveness, PARO leans heavily on passive cuteness and touch-based interaction. This raises the question: could a lower-cost alternative achieve similar emotional benefits without the excessive hardware investments?

Qoobo: Minimalism Done Right

Qoobo, a robotic cat tail pillow, is perhaps one of the most efficient robotic animal designs. It distills the essence of animal companionship down to one core feature—the tail's response to touch. While it lacks a face, sound, or other interactive elements, its ability to subtly react to human presence and movement is enough to create an emotionally engaging experience. Qoobo proves that even without simulating a full animal, a robotic creature can still feel alive and comforting.

Aibo: Rich Features, but Could Be More Animalistic

Sony's Aibo has long been a flagship example of robotic pets. It boasts impressive hardware, advanced AI capabilities, and expressive interaction. However, its robotic appearance—while futuristic and sleek—sometimes works against its ability to be perceived as an "animal." Aibo’s LED eyes and metal-plastic body emphasize its technological nature, which can prevent users from fully immersing themselves in an animal-like relationship. This raises an interesting design challenge: while Aibo is highly interactive, could it have been more successful if it embraced a more organic form?

Furby: Overly Anthropomorphized?

Furby is an early attempt at interactive robotic pets, but its strong anthropomorphic design decisions—blinking LED eyes, human-like speech patterns—place it in an ambiguous zone between toy and companion. While its appeal lies in its interactivity, Furby's approach suggests that robotic animals designed for long-term companionship should lean more towards natural animal behaviors rather than exaggerated, cartoon-like features.

The Role of Fur and Texture in Robotic Animals One of the most significant differences between humans and animals is fur. Softness and tactile engagement are crucial elements that enhance bonding between humans and animals. Unlike plastic or metal surfaces, fur-covered robotic animals provide warmth and physical comfort, making them more approachable.

However, fur needs to be designed thoughtfully. GUA's fur-based design follows several principles:

1) Layered and Segmented Fur: Instead of a single, continuous fabric covering, GUA's coat is made of separate, detachable layers that can be individually replaced or adjusted. This design prevents the fur from getting caught in mechanical joints and allows for easier maintenance.

2) Irregular and Varied Lengths: Unlike human hair, which is uniform and concentrated on specific areas, animal fur grows in different directions and lengths. By designing a robotic animal's fur to be slightly asymmetrical and "messy," we reinforce the impression of natural randomness rather than mechanical precision.

3) Color Variation: Rather than solid, uniform colors (which are more common in human clothing), natural animals often have gradients, patterns, and mixed tones. By incorporating these into robotic fur design, we create a more organic and lifelike appearance.

4) Internal "Muscle" Padding: Beneath the fur, soft padding is used to create a layered, muscular feel, preventing the rigid mechanical structure from being too obvious upon touch.

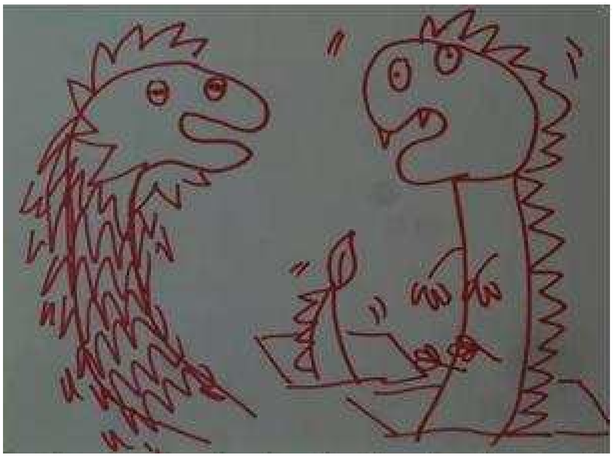

Figure 65 GUA2.0 sketch

Figure 66 GUA2.0 with Jaw new design

6.4 By making GUA 3.0

6.4.1 A lot of GUAs

Through the process of designing and developing GUA, I gained hands-on experience in how to express animal behavior in a minimalist robotic form—essentially a robotic arm given life-like movement. This experience laid the foundation for what I now call the Many GUA project, an attempt to explore how robotic animals can evolve from a simple, jointed structure into more complex and expressive forms.

Just as Amphioxus is regarded as the model species for studying vertebrate evolution—a primitive but functionally rich organism from which more specialized species evolved—GUA serves as a baseline form for robotic animals, evolving into multiple specialized versions with different structures, functions, and expressive capabilities. The Many GUA project explores how robotic animals might expand beyond their initial, simple form—gaining ears, wings, tails, eggshells, and even symbolic flame effects—to become increasingly diverse in both behavior and function.

Figure 67 Many GUA

The Many GUA project introduces multiple variations, each focusing on different aspects of robotic animal evolution. These variations explore how changes in structure, aesthetics, and behavior influence human interaction, perception, and usability. Below are some key members of this expanding family:

6.4.1.1 LONG GUA & FROGUA: Changing Body Proportions

One of the first experiments in Many GUA was altering the number and length of joints, leading to two distinct forms:

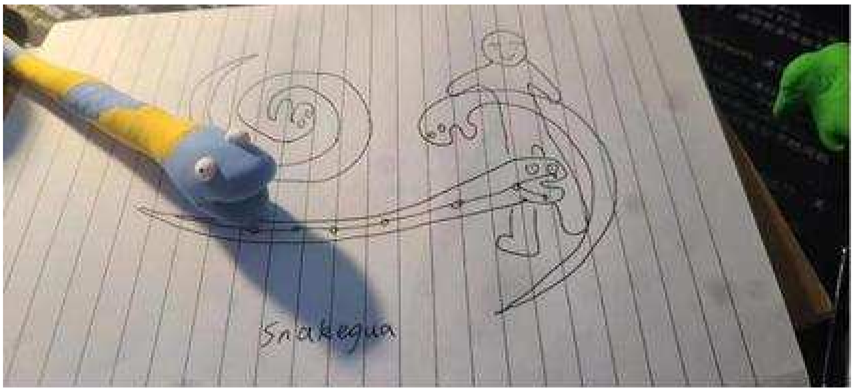

Figure 68 SNAKEGUA

LONG GUA: With an elongated, snake-like structure, this version explores how length affects movement and interaction. While increased flexibility allows for more expressive movements, new challenges arise—entanglement risks, locomotion control, and stability concerns.

FROGUA: A compact and chunkier GUA, resembling a frog. By reducing the number of joints, FROGUA has a more solid and stable form, but at the cost of movement fluidity. This variation explores whether a bulkier robotic animal enhances the perception of physical presence and stability or limits interactive richness.

These variations highlight an important question in robotic animal design: Does increasing body length make the robot more capable, or does it introduce unnecessary complexity?

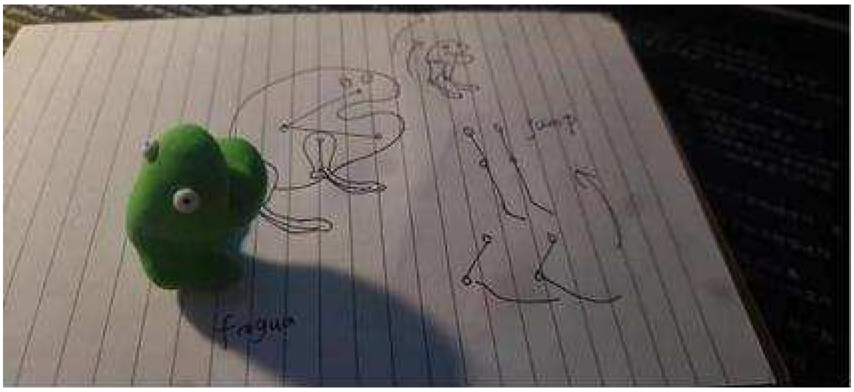

Figure 69 FROGUA

6.4.1.2 FIREGUA: Expressing Aggression Without Harm

FIREGUA is a dramatic, visually striking GUA inspired by fire and dragons. This version explores how a robotic animal can express non-physical aggression—anger, frustration, or excitement—without actual mechanical force. Instead of biting or striking, FIREGUA displays a glowing flame effect inside its mouth as a warning signal, similar to how real animals use body language, coloration, and vocalizations to communicate aggression.

Figure 70 FIREGUA

Additionally, FIREGUA features decorative pink flowers on its head, symbolizing intelligence and personality—a nod to how some intelligent animals (such as crows, elephants, and primates) decorate themselves with natural elements. This raises interesting possibilities for robotic animals to customize their own appearance, potentially even adapting their external look over time based on interaction history.

6.4.1.3 EGGUA: The Egg-Like Companion

EGGUA takes inspiration from KEEPON and traditional tumbler toys, featuring a large, stable egg-shaped base that both hides internal electronics and justifies its lack of independent movement—EGGUA is "a baby inside an egg." This design introduces new physical interaction mechanics:

Instead of walking, EGGUA wobbles and rocks when nudged, similar to a Weeble toy, making it an appealing fidget interaction.

The "egg" can be rolled, tapped, and tilted, adding an element of playfulness while avoiding the complexity of legged locomotion.

This variation emphasizes the importance of designing robotic animals with clear interaction metaphors—rather than trying to force walking or mobility, sometimes an alternative form of movement creates a more natural and intuitive experience.

Figure 71 EGGUA

6.4.1.4 GUATTERFLY: Wings for Social Distance

GUATTERFLY introduces mechanical wings, which alter both its social dynamics and interaction appeal:

Figure 72 Figure 71GUATTERFULY

The wings provide motion-based expression, giving GUATTERFLY additional non-verbal communication cues.

Unlike other GUAs, which are designed to be hugged or physically held, the wings create a psychological and physical barrier, reducing immed

This design could be used for public robotic animals, where maintaining a respectful "social distance" between users and the robot is beneficial.

This version raises an interesting design principle: Physical form can shape social expectations. If a robotic animal looks soft and compact, people instinctively want to hold it, but if it has a more visually "free-moving" form, it encourages observational interaction rather than direct touch.

6.4.1.5 DOGUA: Animalistic Expressiveness Through Ears

DOGUA introduces silicone-covered ears and a Keepon-like soft body. This version explores how animal ears function as expressive communication tools:

Figure 73 DOGGUA

Ears can perk up, droop, rotate, and flick, providing subtle but effective emotional cues.

The soft material allows for safe, close physical interaction, making DOGUA ideal for tactile engagement, such as petting and hugging.

This highlights another key consideration in robotic animal design: What sensory channels are best for conveying emotions? While human robots rely on facial expressions and voice, robotic animals can use ears, tails, posture, and movement patterns to achieve the same effect.

6.4.1.6 GUALIC & STARGUA: Social and Group Dynamics

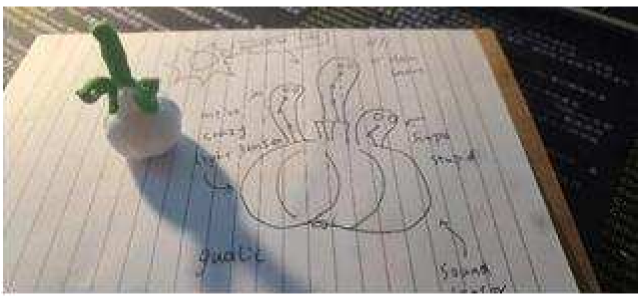

Figure 74 GUALIC

These two variations introduce multiple GUAs interacting together, either as:

GUALIC: A cluster of three distinct GUAs with different personalities, showcasing group behavior and inter-individual dynamics.

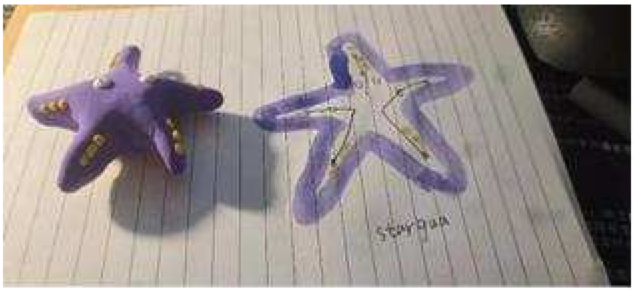

Figure 75 STARGUA

STARGUA: A single robotic animal with multiple arms, offering richer multidirectional movements and expanded interaction options.

This concept opens up fascinating opportunities for robotic animal self-explanation—real animals interact differently with each other and with humans. By having multiple robotic animals display unique relationships among themselves, we can create more immersive and believable social behaviors.

Figure 76 Many GUA sketch

Ultimately, the Many GUA project lays the groundwork for a broader framework of robotic animal diversity, moving beyond the conventional idea of simply replicating real animals. The next steps could involve exploring bioluminescent or color-changing skins for richer expression, refining adaptive behavior models that evolve based on user interactions, and developing flocking behaviors where multiple robots operate as a coordinated group. This iterative process mirrors the evolutionary pathways seen in nature—starting with a simple, foundational organism and gradually diversifying into specialized species suited for different environments and social roles. Rather than aiming for a single, definitive robotic animal, Many GUA embraces modularity, adaptability, and creative variation, providing a scalable approach to designing future robotic companions that are not just functional, but also emotionally compelling and socially engaging.

6.4.2 GUA behavior and action design

Principle of System Structure: Perception, State, and Behavior in Robotic Animals

When I create robotic animals, my goal is not simply to build an imitation of a real creature, but to construct an entity that feels like an animal in interaction—even if it is ultimately a machine. The purpose is to provide city dwellers with a way to engage in human-animal relationships despite the constraints of urban life. These robotic animals are not just passive objects; they move, react, and even develop their own biases over time. Their bodies are strong and furry, their movements clumsy and stubborn, and their minds simple yet opinionated.

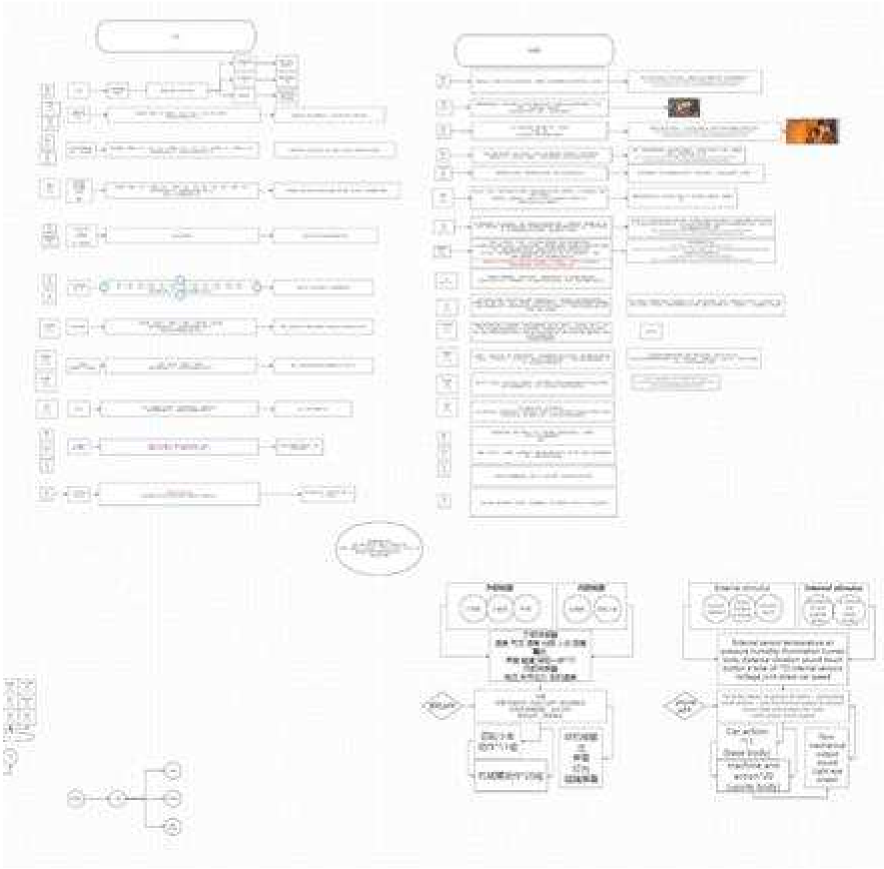

Figure 77 Structure Sketch

A real animal senses, moves, and makes decisions—so the robotic system must do the same.

To achieve this, I use a three-layered system structure:

1. Performance presets based on current state – Ensuring the robotic animal reacts in a natural, predictable way.
2. Comprehensive judgment system ("the brain") – Interpreting stimuli and determining appropriate responses.
3. Sensory weightings for judgment – Prioritizing different types of sensory inputs based on context.

This structure forms the basis of my Perception, State, and Behavior model.

The robotic animals I designed don't use machine learning. They don't rely on cloud computation. They don't "talk back" like a chatbot or try to understand language.

Instead, their intelligence lies in the way they move. Their behaviors emerge from a simple but layered internal system:

Sensors: They use basic sensors (like light, sound, proximity, and temperature) to feel what's around them.
Internal State System: These inputs feed into an internal state model—comprising three key parameters: emotion, activity, and motivation. These aren't hidden values. They're literally how the robot "decides" what to do.

Behavior Mapping: Each combination of internal states is mapped to a small set of behaviors. For example, if motivation is high but activity is low, it may trigger a “searching” behavior. If motivation is low and emotion is low, it might just curl up or stay still.

Randomized variation: Even when in the same state, the system randomly chooses from 2–4 possible behaviors. This adds unpredictability—not as a trick, but as a functional expression of liveliness.

You could call it “simple AI.” But I think of it more like weather—a pattern that’s constantly shifting, based on internal energy and external changes.

There’s no direct script for each interaction. Instead, what the robot does depends on what it senses and how it feels in that moment. This isn’t high-level intelligence. But it’s enough to make people wonder, “Is it okay? What does it want?”

That wonder is the whole point.

Sensor Input	Emotion	Activity	Motivation	Behavior Example
Loud noise	↓	↑	↑	Dart away and hide
Human nearby	↑	↑	↑	Approach and nuzzle
Dim light	→	↓	↓	Curl up and stay still
Sudden movement	↑	↑	↓	Flee, then pause

State: The Core of Animal-Like Behavior

Through my research in animal behavior, I identified three definitive factors influencing an animal’s actions:

1) Emotion (E) – Does the animal feel happy, neutral, or upset?
2) Activity (A) – Is it active, passive, or in between?
3) Motivation (M) – Is its behavior intentional or unconscious?

Each of these dimensions determines the way the robotic animal expresses itself, resulting in natural and varied interactions.

Emotion (E)

The emotional state is divided into three levels:

- 1 – Upset (e.g., anger, stress, fear)
- 2 – Neutral (e.g., calm, indifferent)
- 3 – Happy (e.g., excitement, affection, satisfaction)

Activity (A)

Activity levels dictate the energy of the movement:

- 1 – Inactive (slow movements, resting state)
- 2 – Intermediate (mild interactions, simple reactions)
- 3 – Highly active (running, jumping, attacking, playing)

Motivation (M)

Motivation determines whether the behavior is intentional:

- 1 – Unconscious behavior (passive, background movements, not directed at a person)
- 3 – Conscious behavior (intentional, focused interaction, active response to people)

Unlike Emotion and Activity, Motivation only has two levels. In previous versions, I used three, but I realized that the distinction between "conscious" and "unconscious" is sufficient—either the robot actively reacts to an external stimulus, or it continues its own independent behavior.

This is a critical element often ignored by social robots—most robotic animals are designed only for human interaction, but real animals spend much of their time doing their own thing. A bird does not need a human to preen its feathers. A cow does not exist just to greet people—it lives its own life, but still reacts when necessary. By emphasizing natural behavior outside of human interaction, the robotic animal gains a stronger sense of free will and independence.

6.4.3 Behavioral Mapping: 18 States for Naturalistic Interaction

By combining three levels of Emotion, three levels of Activity, and two levels of Motivation, I created a total of 18 behavioral states (3×3×2 = 18). (Earlier versions had 27 states, but reducing Motivation to two levels streamlined the system without losing behavioral depth.)

Each state is defined as a three-number code (A, E, M), representing Activity, Emotion, and

Motivation. Some examples:

- Attack (3,1,3): High activity, negative emotion, intentional behavior – aggressive response to threats.
- Shy (1,3,3): Low activity, positive emotion, intentional behavior – a coy, hesitant but affectionate interaction.
- Wander (2,2,1): Medium activity, neutral emotion, unconscious behavior – the robotic animal is moving without a specific purpose, creating a natural "idle state".

This mapping ensures fluid, organic behavior where the robotic animal neither feels like a rigid automaton nor an overly predictable programmed toy. By structuring interactions through these three dimensions, it creates a consistent yet unpredictable behavior model—just like real animals.

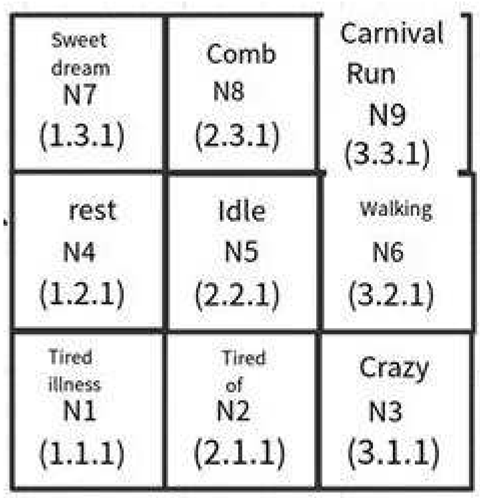

Figure 78 Robot behaviours group

Figure 79 Robot behaviours group

6.4.4 System

As mentioned earlier, the control system and overall structure of GUA 3.0 have gradually become more complex and refined. Through multiple rounds of testing, we continuously adjusted functional modules and control structures, allowing the circuit board design to become more integrated, smaller, lighter, and more stable. The diagram below illustrates the final version of the control system architecture, along with three key iterations. These iterations clearly show how we transitioned from an early experimental prototype to a more reliable and efficient system.

The earliest version was a breadboard-based prototype, which provided great flexibility for early functional validation but suffered from severe stability issues—especially after being transported across countries, as all the wiring would inevitably become disorganized. This setup, while convenient for modifications, was far from practical for long-term use, particularly when extensive testing or demonstrations were required.

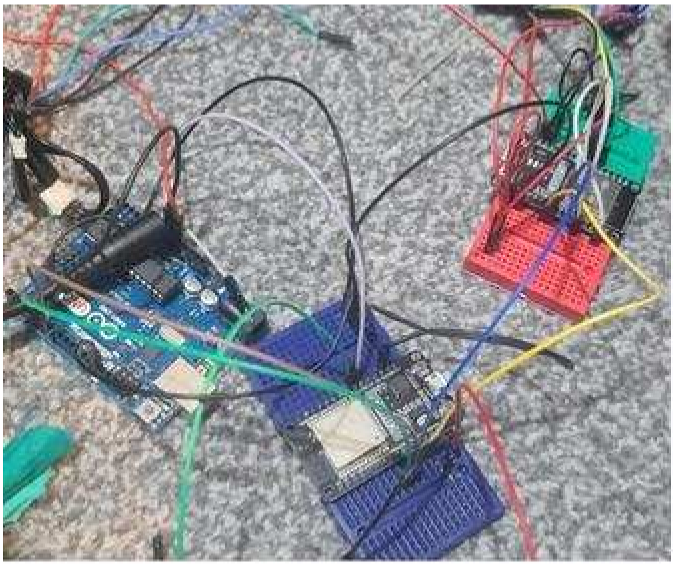

Figure 80 first test kit wires set

Building on this, we developed the second version, nicknamed “the green five-story building.” This iteration became the longest-used and most critical version, serving as the primary system for all human-robot interaction tests in this study. Compared to the first version, it significantly improved stability, durability, and maintainability while allowing for the integration of additional sensors, enhancing GUA’s perception capabilities and movement expressiveness. However, this version still had physical size constraints—while its functional modules were well-defined, it required extensive external wiring, limiting its suitability for compact robotic platforms.

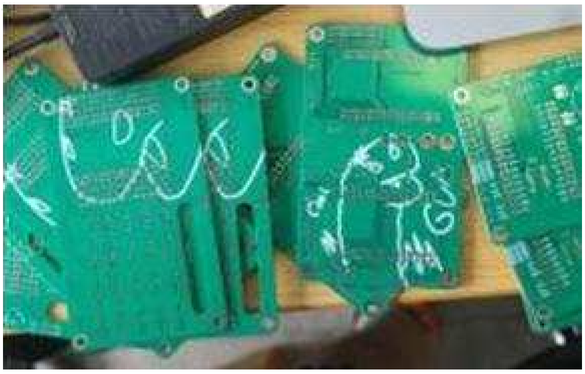

Figure 81 Second version of PCB board design in 5 chips

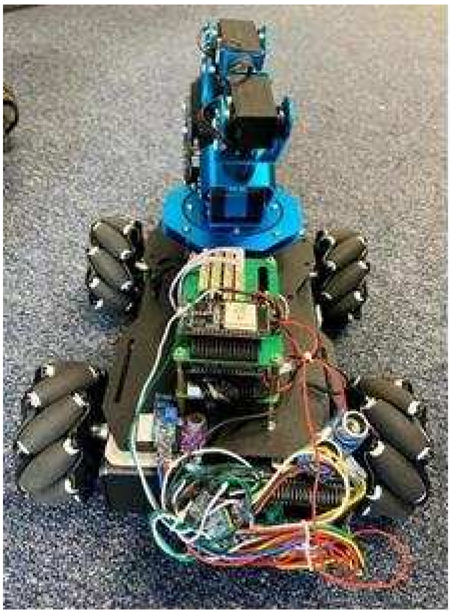

Figure 82 How it looks like on robot

Ultimately, the latest integrated version marked a significant breakthrough. This version consolidated the previously separate five functional modules into a single circuit board, while dramatically reducing the size of the sensors and utilizing a custom-designed PCB layout. As a result, it eliminated excessive external wiring, improving stability, safety, and overall aesthetics. This optimization not only allowed for a more compact design, but also enabled GUA to support higher voltage levels, which in turn made it possible to integrate a sound module that was previously unfeasible due to power limitations. Consequently, GUA can now use predefined sounds and specific auditory feedback mechanisms to enhance interaction, making its behavior more lifelike—no longer relying solely on physical movement to convey emotions.

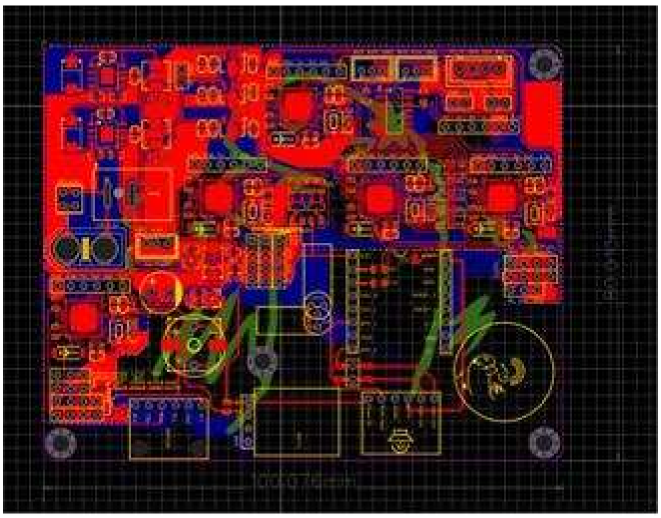

Figure 83 PCB Design

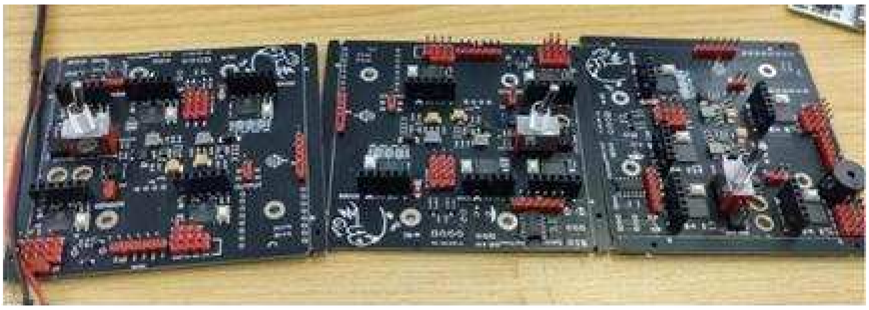

Figure 84 PCB Design Most new version of System

This series of optimizations not only improved GUA's usability but also provided valuable insights for future robotic development. Stability, integration, modularity, and maintainability are crucial factors in the evolution of robotic hardware, while well-optimized sensor placement and efficient power management can significantly enhance interactive experiences.

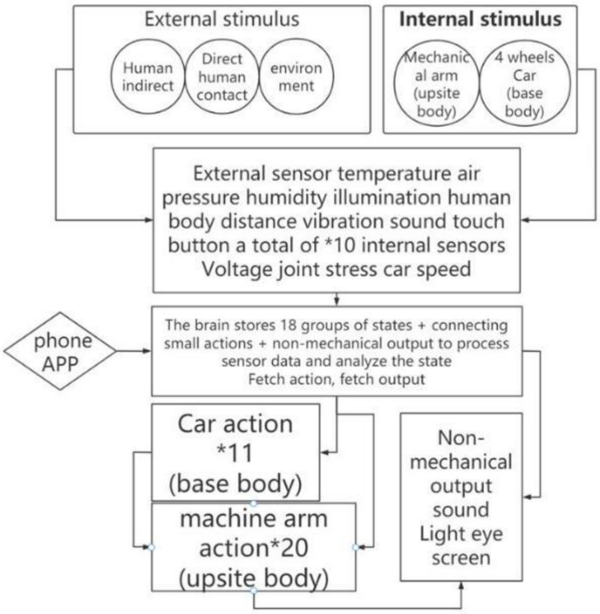

Figure 85 GUA system

In addition, I collaborated with a sound designer to create a custom audio set for GUA, ensuring that the sounds aligned with its character and behavioral expressions. This process incorporated modern electronic music design techniques while also integrating the organic texture of real animal sounds, striking a balance between artificiality and natural authenticity.

However, as previously mentioned, the speaker system posed a technical challenge due to incompatibility between its power requirements and the robot's voltage constraints. This issue has yet to be fully resolved, meaning that in the user testing sessions detailed later in this paper, GUA was tested without sound.

Interestingly, despite the absence of sound in the test version, many users frequently mentioned “sound” as a missing element in their feedback. Their sensitivity to this factor highlights the crucial role that audio plays in shaping the identity of robotic animals. It suggests that beyond physical appearance and movement, sound contributes significantly to how people perceive an artificial creature’s presence, emotional state, and lifelike qualities. This observation reinforces the importance of integrating expressive audio feedback into future iterations, not only for enhancing realism but also for deepening human-robot emotional engagement.

6.5 The structure and material

At its core, GUA is a robotic monster, a machine-animal hybrid that fuses behavioral traits from reptiles, birds, and other creatures into a single expressive entity. Its distinct movement patterns are heavily influenced by large predatory birds and ambush reptiles, with most of its characteristic behaviors reflected in its giant claw, which functions as a mechanical arm.

GUA’s mobility is provided by a four-wheel electric motor base, allowing it to perform a variety of movements inspired by both vertebrates and invertebrates. With a combination of mechanical arm articulation and wheeled movement.

Although the robotic arm and wheeled base are controlled separately, careful coordination between the two creates the illusion of a fluid, lifelike being. To avoid the stiffness commonly associated with robots, GUA does not simply transition from one pose to another—instead, it incorporates subtle micro-movements and transitional animations.

Beyond the 18 primary behavior states described earlier, additional transitional movements such as:

Turning left and right naturally rather than snapping abruptly.

Shifting weight forward and backward when preparing to move.

Gradual posture changes to simulate tension, relaxation, or anticipation.

These additional movements allow GUA to blend behaviors smoothly, reducing the robotic "jumpiness" often seen in programmed movement transitions. Instead of robotic precision, GUA aims for an organic unpredictability, making its actions appear more intuitive, like a real animal reacting moment to moment.

Figure 86 PCB GUA pokes forward like a snake

Soft Materials: From Uniform to Structured Coverings

In GUA 1.0, its entire body was soft and uniform, resembling a sea cucumber, without distinct head or body segmentation. This meant fillings could be evenly distributed without additional support. However, as GUA evolved into GUA 2.0, featuring a distinct head with an articulated jaw, new material challenges arose:

Misalignment & Deformation: Using the same soft material throughout caused the head and jaw to lose alignment, often leading to crooked movement or even detachment.

Risk of Mechanical Exposure: Without proper material support, the plush covering could slip, revealing the hard metal components beneath, which could be both visually unappealing and potentially hazardous.

To solve this, GUA 2.0 introduced a layered material system:

"Leather-Wrapped Muscle" Approach:

The core structure was wrapped with a firm but flexible base layer, simulating muscle texture while reinforcing structural integrity.

Multi-layer cloth strips were used to create a dense, soft, and flexible coat, hiding mechanical joints while allowing smooth movement.

Segmented Covering Design:

Instead of a single fabric piece, each section of the body (head, torso, base) received an independent cover, preventing dislocation during movement.

A thin covering cloth at each segment joint prevented fur from getting caught in moving parts.

Intentional "Weird Skin Color":

A bright red internal layer was used not for aesthetics, but to serve as a visual indicator of structural integrity.

If too much red was exposed, it signaled movement issues or material misalignment, allowing for quick real-time corrections.

Figure 87 GUA2.0 head dropped at event

Figure 88 GUA hand made head

Figure 89 Hand made cover for head

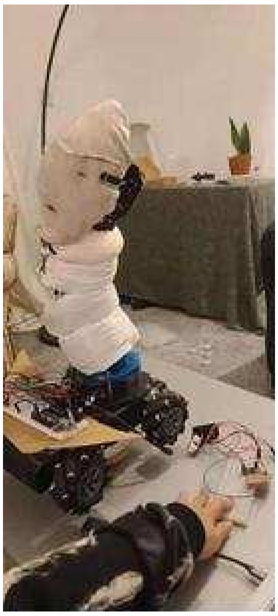

Figure 90 Hand made body with sponge

Figure 91 Some body design test

Figure 92 Fire proof material

Figure 93 New design for head

Figure 94 3D print Head

Figure 95 GUA

Chapter 7 User Test—Focus groups

In this chapter, I observe what happens when people spend time with the robotic animals I made. Some stroked them without speaking. Some tried to train them. Some smiled, and some just stared.

I wanted to know: would they feel something? Would they project stories, or care, or just curiosity? Most of all, I wanted to see whether GUA could offer a kind of presence—not perfect, not flashy, just there.

This chapter doesn't offer conclusions. Just moments

The primary goal of this study is to evaluate how non-expert users perceive and interact with GUA, a robotic animal designed to simulate aspects of real animal companionship while maintaining its own distinct artificial characteristics. Unlike traditional robotic pets, which often mimic specific real-world species, GUA adopts a more abstract, monster-like form, designed to evoke emotional engagement through movement, texture, and behavior. By conducting this study with non-specialist participants, such as psychology students and faculty members, the aim is to capture the intuitive, everyday human experience of interacting with robotic animals, rather than focusing solely on technical evaluations from roboticists or engineers. The questionnaire is structured to explore three key areas: (1) users' categorization and perception of GUA as an animal, a robot, or something else entirely, (2) their emotional and cognitive relationship with GUA, including the extent to which they believe it exhibits consciousness, emotions, and preferences, and (3) their willingness to interact with GUA in different scenarios, as well as their expectations for an ideal robotic animal companion.

By collecting responses across these dimensions, the study seeks to address several fundamental questions: How much of an "animal identity" do users assign to GUA? What specific features (e.g., movement, sound, touch) contribute to—or detract from—this perception? Can GUA create an emotional bond similar to that of a pet, or do users see it primarily as a tool or an entertainment object? Furthermore, exploring user attitudes toward GUA's behavior and presence provides insights into how people navigate relationships with artificial lifeforms—whether they perceive robotic animals as companions, interactive machines, or something in between. The findings from this study could have broader implications for the design of social robots, particularly in public or private settings where robotic animals may be introduced as long-term companions. The study may also reveal potential ethical or psychological concerns, such as whether people feel uneasy about robotic animals imitating emotions, or whether they anticipate negative consequences from prolonged interaction. Ultimately, these insights will inform future iterations of robotic animals, helping to refine their design, interactivity, and social acceptance.

The testing of robotic animals is not just about their technical performance—it is fundamentally about how humans react to artificial creatures that exhibit animal-like behaviors. Real animals are compelling because they possess autonomy, unpredictability, and selective social preferences. They don't behave like machines with set responses; instead, their interactions vary based on mood, past experiences, and environmental context. This element of spontaneity and independence is crucial in making human-animal relationships feel real. The challenge for robotic animals is whether they can generate a similar experience, not just through movement but through behavioral patterns that evoke the same cognitive and emotional responses in humans.

Over time, the GUA prototypes have been brought into various public spaces—from university halls to children's workshops. Children don't need an explanation. They just gather around it, jump, laugh, and invent relationships on the spot. The robot has survived repeated use, collisions, aggressive hugs, and emotional storms. Its fur covering occasionally falls off—and when it does, interest plummets. The illusion is broken. But while the body matters, it's not the fur alone; it's the presence.

People treat it as an animal. No one calls it a toy. They approach it the same way they would approach a strange small creature on the street: with caution, then warmth, then stories.

One test involved bringing GUA to a Russian-language school. The children there had different cultural references and didn't share a native language with me. But the reaction was still instinctive. They were more cautious at first, more precise in their questions—especially about the technology behind it—but that didn't stop them from slowly reaching out, petting it, and eventually giggling when it wiggled.

Even adults, even when told it's a robot, still interact with it as something alive. Not because they believe it, but because it feels better to pretend.

These reactions shaped what comes next. A collaboration with autism researchers in China is already planned, where GUA and its larger cousin—a snake-like robotic creature—will be introduced to children with sensory processing needs. The soft body, the pressure response, and the invitation to touch may help regulate anxiety or provide emotional relief.

This is not just about design. It's about letting machines step into the emotional space normally reserved for pets, plush toys, or even fictional characters—not to replace them, but to offer a different kind of presence. One that can be strange, imperfect, but still welcome.

This study is particularly informed by Barber & O'Neill's (2023) research, in which Anne played a significant role. Their work compared human interactions with real dogs versus robotic dogs, investigating how people emotionally engage with robotic pets versus living animals. Their findings suggest that while robotic dogs can elicit attachment, the depth and nature of that attachment are significantly influenced by perceived autonomy and unpredictability. If a robotic animal behaves in a way that is too predictable, it feels artificial. Conversely, if it demonstrates individual preferences, occasionally ignores commands, or reacts unexpectedly to different people, it becomes more believable as an independent entity rather than just an advanced toy.

Konok et al. (2017) explored how human-animal relationships rely heavily on nonverbal cues, spontaneity, and behavioral variability. They emphasized that real animals are not merely reactive—they initiate interactions, express emotions unpredictably, and display selective social bonding. This research supports the idea that a robotic animal should not respond the same way to everyone—it should form preferences, recognize individuals, and sometimes exhibit behaviors that are difficult to explain. Anne's contributions to Barber's study align with this perspective, highlighting that perceived autonomy and selective responsiveness are key factors in making robotic animals feel more "alive."

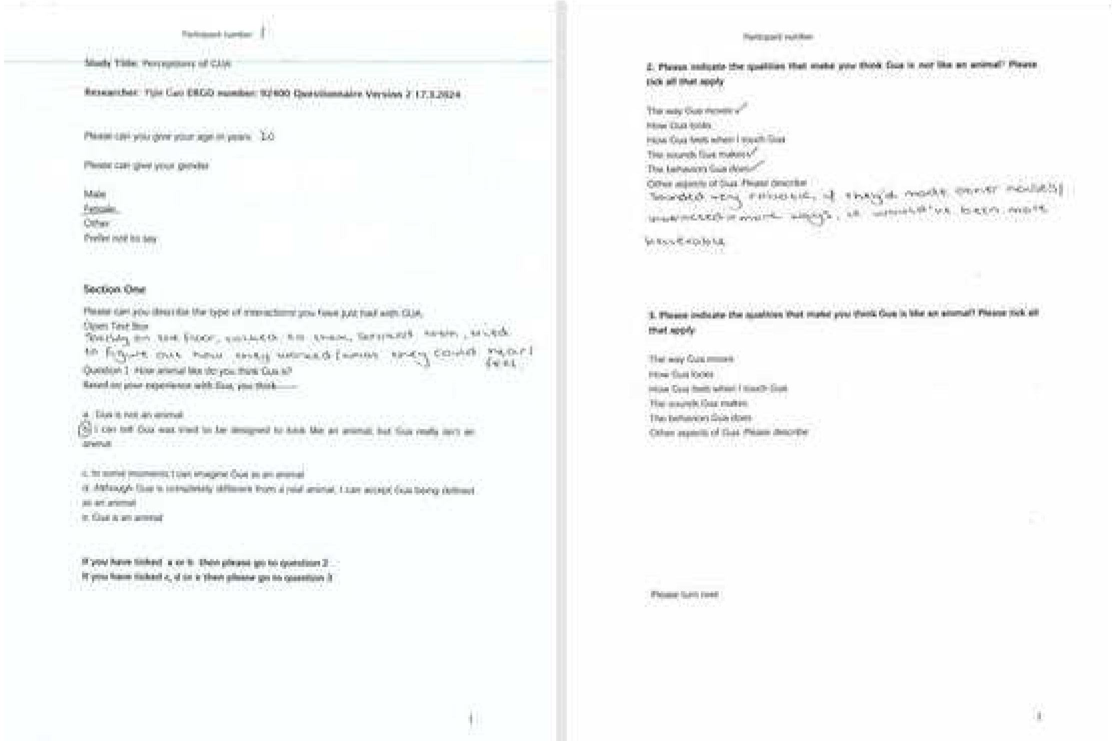

Figure 96 Test result number 1

Figure 97 Test result number 1 the other page

Chapter 8 Summary

This chapter looks back at the questions I asked, and the paths they opened. Some things became clearer. Others stayed a little blurry—and maybe that's alright.

I reflect on the limits of what I made, and the strange tenderness of trying to make something nonhuman feel welcome in a human world.

I have always been a passionate enthusiast of human-animal interactions, and while this research journey may seem to have begun in recent years, the truth is that it has likely been unfolding since childhood. When I was in the fourth grade, I wrote a story about a robotic dog named "卡龙 (CARDRAGON)"—a futuristic companion that took me on a journey through a school of the future, only for me to wake up and realize it had all been a dream. Looking back, maybe that dream was never truly just a fantasy—it was the seed of my lifelong fascination with creating artificial beings that could interact with humans as naturally as animals do.

My academic and research path could best be described as "chaotic"—an unpredictable but ultimately meaningful sequence of explorations. I started with an undergraduate degree in aquaculture, drawn by my deep love for observing and understanding animal behavior, particularly in fish. Then, my passion for art and visual storytelling led me to pursue a master's degree in design, where I explored how form, aesthetics, and interaction shape people's experiences with objects and environments. It wasn't until my PhD that I fully embraced my fascination with robotics, teaching myself mechanics and electronics through countless experiments, collaborations, and sheer trial and error. What started as an exploration of robotic animals soon expanded into a larger journey of understanding how artificial beings can perceive, move, and form relationships with humans and their surroundings.

This research is neither the beginning nor the end of that journey—it is just one point in an ongoing evolution. In the future, I aim to further explore bio-inspired robotics, creating robots that not only mimic animal behavior but also embody the adaptive, autonomous, and emotionally responsive nature of real creatures. My work will continue to be shaped by my interests in cognitive robotics, particularly in designing robots that develop unique preferences, learn from interactions, and exhibit dynamic, evolving behaviors over time. Additionally, I am interested in soft robotics and materials that simulate organic textures and movement, ensuring that robotic animals feel as real in **touch antouch and motion as they do in behavior. Beyond robotic animals, I am also intrigued by the potential of AI-driven interactive systems, particularly how social robots can serve in psychological and emotional support roles—whether for companionship, therapy, or even as partners in creative expression.

Perhaps, deep down, I have always been chasing the same goal: to bridge the gap between human perception and artificial life, to make robots feel more like creatures and creatures feel more understood. Whether it was my childhood dream of CARDRAGON, my early fascination with fish behavior, my experiments with robotic animals, or my future explorations into cognitive and bio-inspired robotics—**all of these paths have converged into the same pursuit: understandingall of these paths have converged into the same pursuit: understanding what it truly means to "be alive" in the eyes of an observer.

Figure 98 Public event

Figure 99 Robot Fight

Figure 100 Mechanical practice

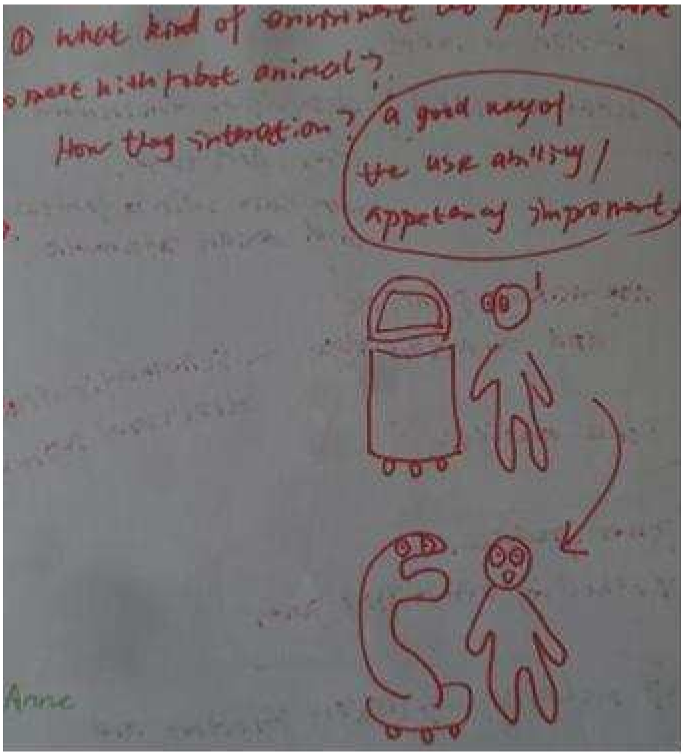

Figure 101 Robot fried

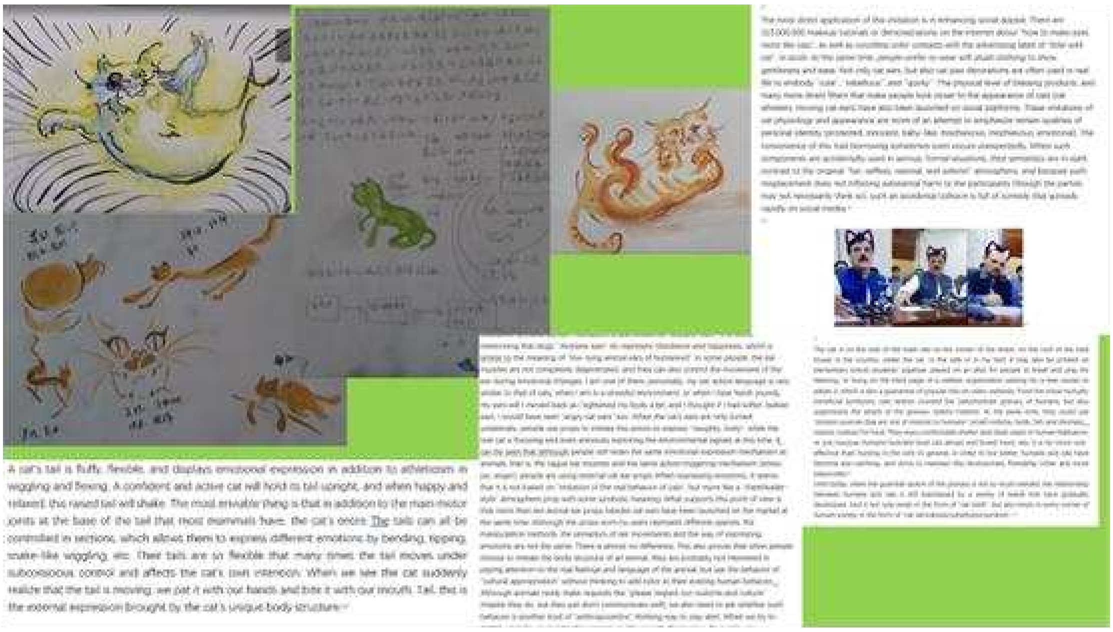

Figure 102 Sketches and Notes on Cat Movements and Cultural Representation

This page combines my sketches of cats, handwritten notes, and excerpts from cultural discussions. It focuses on the tail and body as central elements of feline expression. A cat's tail is flexible and segmented, capable of subtle gestures—shaking, curling, or tipping—that reveal emotions in ways human bodies cannot. This difference between species is exactly why people are fascinated by cats: their movements embody another way of sensing and reacting to the world. In urban life, where contact with animals is limited, such visible animal traits become a substitute for cross-species connection, like a small but sharp taste that interrupts a bland diet. The attraction is not simply about cuteness, but about accessing an emotional and perceptual logic different from our own. Yet in regions where people already live closely with animals, cats often lose this symbolic value and become little more than luxury companions, less central to everyday life. In this way, the cat is both an animal with unique physiological cues and a cultural artefact shaped by human environments and desires.

Robotic Dog Design and Behaviour System

These three pages together document the path from mechanical prototyping to behavioural mapping and finally to motion analysis. The first stage explored how simple structural tests and modular coverings could already carry signals of "animalness." The second translated canine anatomy and everyday interaction moments into a practical state library that the robot could follow. The third refined this into short, chainable motion clips drawn from repeated sketches, proving that lifelike presence comes from subtle shifts rather than theatrical displays. Taken as a whole, this series shows how I built a robotic dog system that stays close to animal logic—rooted in anatomy, expressed in posture, and made believable through small but meaningful movements.

Figure 103 Prototyping of Robotic Dog Body and Head Expressions

This page records my early attempts to build a robotic dog, starting with the mechanical frame and experiments with different head shapes. I tested clay models, cartoon-like faces, and mechanical fittings to see how much expression could be conveyed through the structure. The sticky notes show how I broke down dog actions into modular groups, so the robot could later combine them flexibly. It was less about “perfect realism” and more about finding which parts of a dog’s body make people feel it is alive.

Figure 104 Mapping Dog Anatomy and Behavioural Modules

This page combines sketches of dog anatomy with large sheets of sticky notes. Each note is a fragment of an idea—about posture, tail movement, or the way a dog approaches humans. Together they form a system of “action groups” that guide how the robotic dog should move. These sketches show how I translated biological structures into mechanical ones, and how human–dog interaction moments (feeding, calling, touching) were simplified into repeatable motions for the robot.

Figure 105 Sketch Studies of Dogs and Motion Analysis

Description: This page gathers my painted sketches and anatomical notes of dogs in different poses—running, curling, or simply watching. By drawing them repeatedly, I analysed which movements express emotion most clearly. Notes around the drawings break behaviours into technical terms: angles, muscle tension, and transitions between states. This stage was about linking observation to design—capturing the essence of dog motion and preparing it to be rebuilt as robotic sequences.

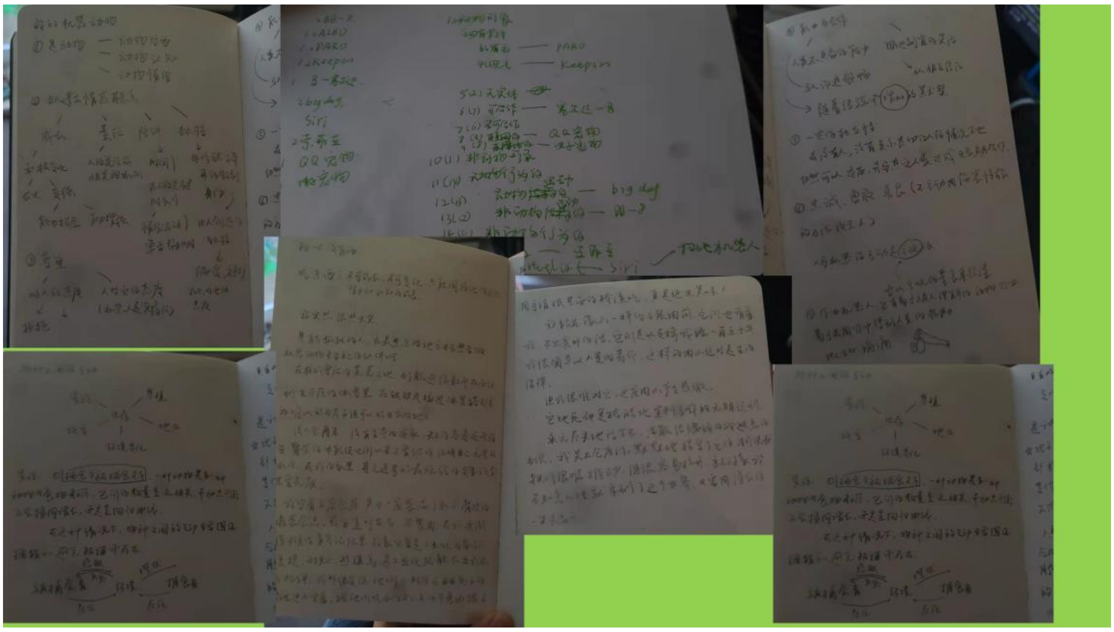

Figure 106 Notes on Literature, Typologies, and Human–Animal–Robot Relations

This page summarises notes on classifying and comparing real animals, virtual animals, and robotic animals. It lists well-known examples such as PARO, Keepon, QQ Pet, and Boston Dynamics' Big Dog, and sketches diagrams that map their roles across social, cultural, and emotional contexts. The notes highlight that animals are not only biological beings but also social and symbolic figures. By contrasting virtual and real animals, I explored how robotic animals could fill the gap of human–animal connections in urban life and take on new positions within human society and culture.

Figure 107 Handmade Sponge Model of the GUA Head

This is a handmade sponge prototype for the GUA's head. The black strap secures it to the mechanical claw, ensuring both stability and freedom of movement. The three-dimensional cutting is tailored to fit the GUA's paw and mechanical frame, allowing the form to stay soft yet structured. This combination of flexibility and shape provided a way to test how coverings could interact with mechanical parts without losing animal-like expression.

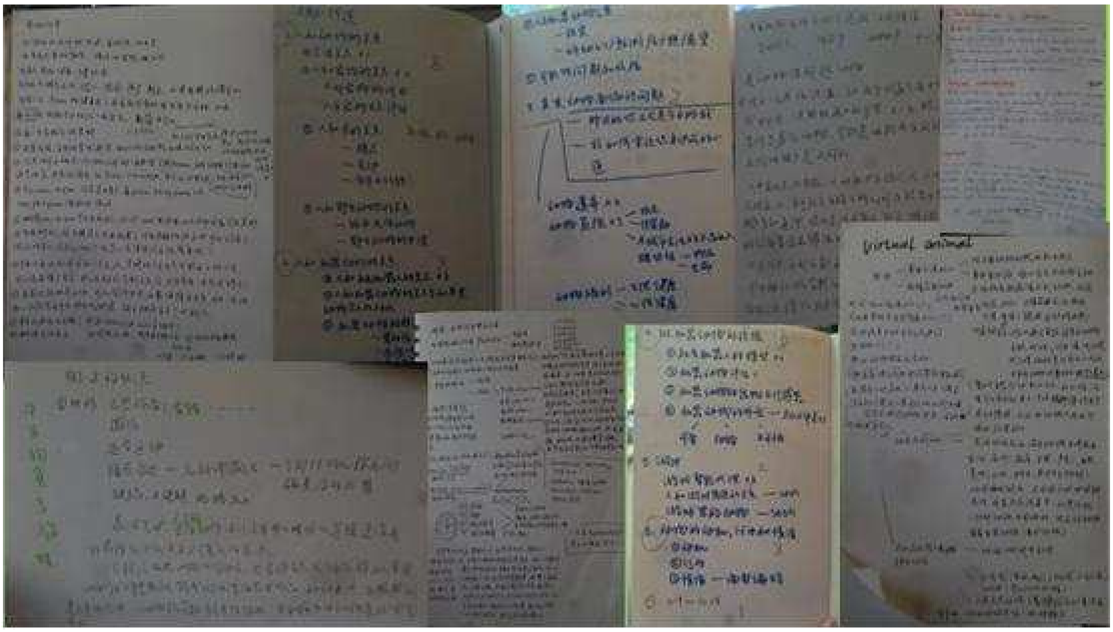

Figure 108 Notes on Real, Virtual, and Robotic Animals

Here I tried to untangle the differences between real animals, virtual animals, and robotic animals. Real animals have bodies and feelings; their reactions are unique and irreplaceable, but also unpredictable and costly. Virtual animals depend on human projection—you can raise a QQ Pet on a screen and feel some comfort, but there's no body, no touch, so it's more of a psychological band-aid. Robotic animals sit in between: they have bodies and they move, but because they are designed, their behaviours can be simplified, exaggerated, or controlled. They are not as wild as real animals, yet not as empty as virtual ones.

Animals in society are never just "animals." They are companions, tools, symbols, and entertainment. For me this breaks down into three levels: function, emotion, and culture. That's the frame I keep in mind: robotic animals aren't just machines, they are also read and used socially.

I also sketched a "human–animal–machine" triangle. My goal is not to make robots that just copy cats or dogs, but to let them find their own place at that intersection. The design path is straightforward: observe the animal → extract a pattern → turn it into repeatable robotic actions. This way the design stays close to animal logic, but is also stable in a mechanical system.

So this page is more than a list of cases (like PARO, Keepon, QQ Pet, Big Dog). It is me asking: why do people need robotic animals at all? My answer: in cities, human–animal contact is often missing. Robotic animals can fill that gap—they can provide companionship, but also push us to rethink what “animal” even means to us.

Figure 109 Group Relations and Miscellaneous Design Concepts

This page explores the dynamics of leaders and followers within animal groups, and how such relationships shape social interaction among animals. By sketching postures and roles in herds, I examined how dominance and submission can be translated into robotic interaction design. Alongside this main theme, the page also records scattered design ideas—variations of eyes, a symbolic “electronic moon,” and a cloud form that carries emotional expression. Not all of these elements entered the prototypes, but together they show the richness of the research and the creative process, combining behavioural observation with symbolic and imaginative experiments.

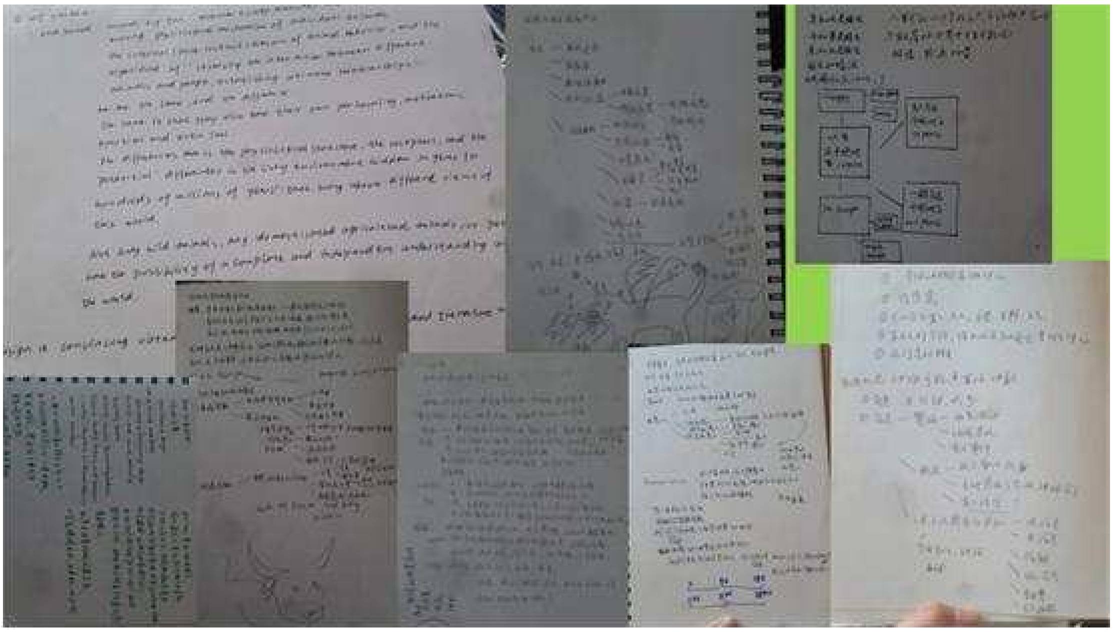

Figure 110 Notes on Animal Perception and Design

This page is me asking: how do animals actually sense the world? Humans keep explaining animals through our own lens, but every species has a different body and sensory system—insects with compound eyes and antennae, dogs with noses and ears, birds through flight and space, while humans put vision on top. That gap means we often misread animals.

I wrote here that wild animals, livestock, and pets all have their own individuality and emotional logic. Their behaviour isn't just stimulus–response; it comes from motivation, cognition, and feeling together. That's why I drew the chain "stimulus → cognition → emotion → behaviour": to remind myself not to skip the middle when designing robotic animals. If the robot only shows external actions without any "sense," it feels hollow.

I also questioned where robots stand between humans and animals. For me, robotic animals aren't about building a dog that is "just like a dog," or making everything transparent for humans. It's about keeping some animal logic. Not every move has to be obvious; ambiguity and hesitation can stay, just as in real animals. That opacity is what gives presence, as if the robot has a mind of its own.

So the point from this page is: animals are independent perceivers, and robotic animal design should respect that. What I'm making isn't a substitute pet—it's a new creature, one that can connect with humans but still holds on to its own world.

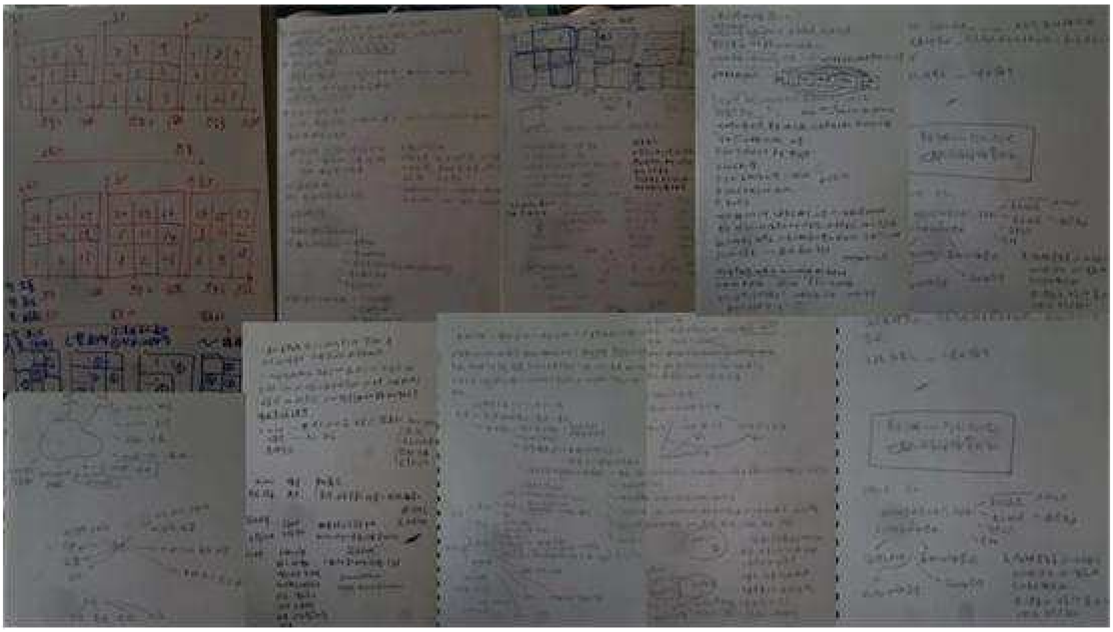

Figure 111 Early System Notes for Emotion–Activity–Agency Model

This page brings together an early sketch of the system design. At the top, the 27-cell grid shows how three axes—emotion, activity, and agency—combine into different states, each linked to a behaviour library. Next to it, flow diagrams outline the process: sensors gather external stimuli, values are normalised and update the three axes, which then map to a state cell and call the corresponding behaviours. To make the output feel closer to animals, I added mechanisms such as thresholds and hysteresis to avoid flickering, and randomness with cool-downs to prevent repetitive patterns. Written notes emphasise that robotic animals should not simply copy human expectations but follow animal logic, where emotions and motivations together drive behaviour. Scattered sketches and diagrams—such as clouds linking "input–emotion–output," or state-change curves—capture the attempt to visualise how information turns into action. Taken as a whole, the page shows the first outline of a full chain: from sensory input, through internal state, to behavioural expression.

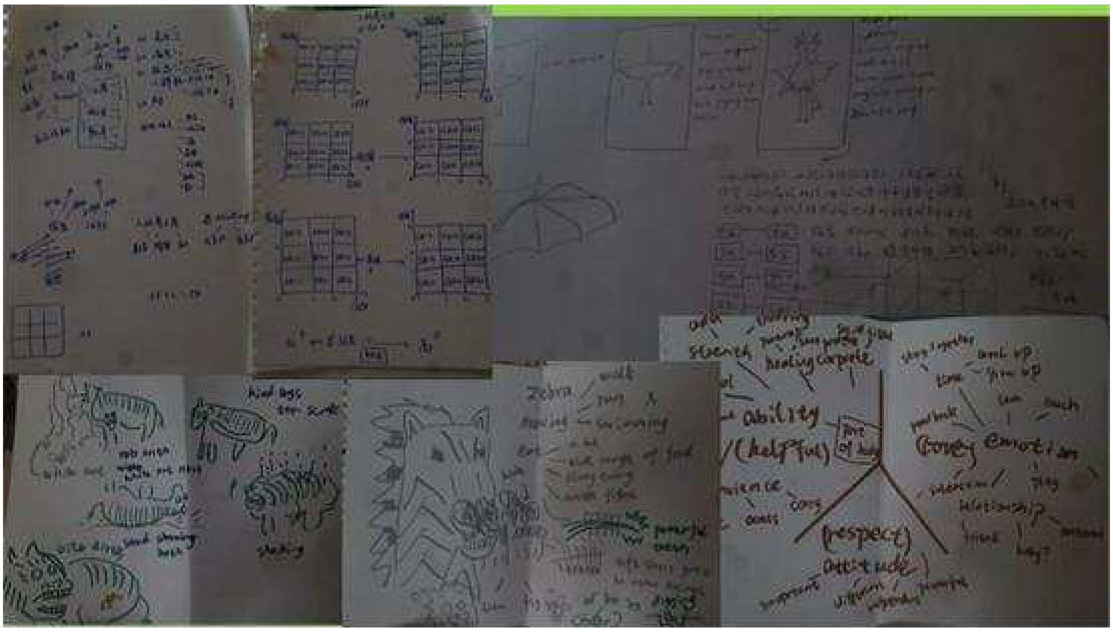

Figure 112 Extending the Model with a Value Framework

This page expands the emotion–activity–agency state grids while also layering in animal observations and a value-based framework. Sketches of zebras, caterpillars, and horse heads show how bodily details—gaits, undulating rhythms, ear and eye positions—communicate emotion and intent. Diagrams of bird flight explore how natural rhythms might be reconstructed through parameter control. Most significantly, the concept map in the lower right sets out a three-part framework of ability, emotion, and respect:

Ability (helpful): what the animal or robot can do, and to what extent it is useful in its environment or to humans.

Emotion (care): whether it can express feelings, create closeness, and convey care in interaction.

Respect (attitude): whether humans grant it status and acknowledge its subjectivity, rather than treating it as a tool.

Together, these three dimensions form a value framework for understanding human–animal–robot relations. The focus is not only on visible behaviours but also on the social and ethical meanings behind interaction. This page shows how my work connects detailed animal observation with systematic modelling and conceptual reflection, placing robotic animals within a broader cultural and societal context.

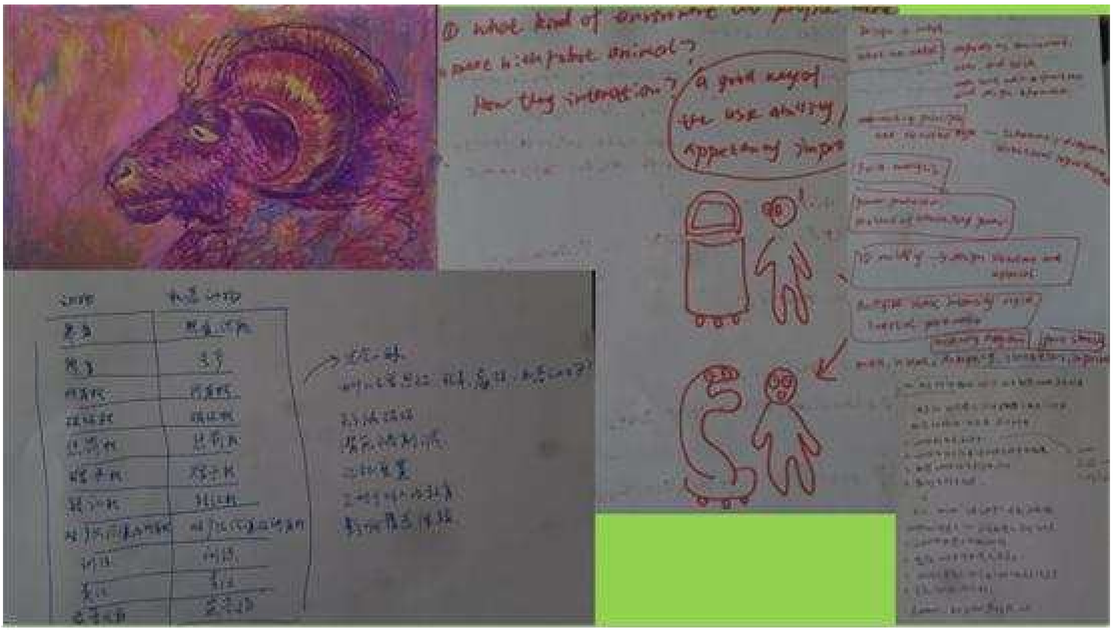

Figure 113 The Difference Between Animal-Shaped and Machine-Shaped Social Robots

This page reflects on the difference in human perception between animal-shaped and machine-shaped robots. The animal drawing and the comparison table link real animals to their robotic counterparts, asking how specific species might be recreated. The red-pen sketches on the right make the contrast clear: a cylindrical, machine-like robot is read as a tool, while an animal-shaped robot is immediately perceived as more approachable and capable of emotional connection. The notes underline my core observation: when robots take animal form, people are more likely to attribute feelings, personality, and social meaning, rather than seeing them as purely functional devices. This page highlights how form and appearance shape social interaction, while also raising the broader question: what kind of “robot animals” do people actually need, and how do these robots relate to the presence of real animals?

Figure 114 Sketches on the Differences and Parallels Between Animals and Robotic Animals

This page explores the distinctions and overlaps between animals and robotic animals. The red-line anatomical sketches show muscles and nerves beneath the skin, but once the fur is added, observers rarely care about what lies inside—they respond to the visible form and behaviour.

This leads to a key point: as long as robotic animals resemble real animals in outward appearance and behaviour, they can elicit similar acceptance and emotional responses. The caterpillar and sea-cucumber sketches investigate how the simplest mechanical structures can reproduce natural rhythms, creating interactive robotic animals with minimal complexity.

At the bottom, a diagram maps the process "sensor → emotion/feeling → behaviour," stressing the importance of an intermediate layer of processing rather than a direct stimulus-to-action link. Together, these notes combine observation and design: highlighting that robotic animals do not need to replicate biological interiors, but must achieve convincing "animalness" through visible movement and responsive systems.

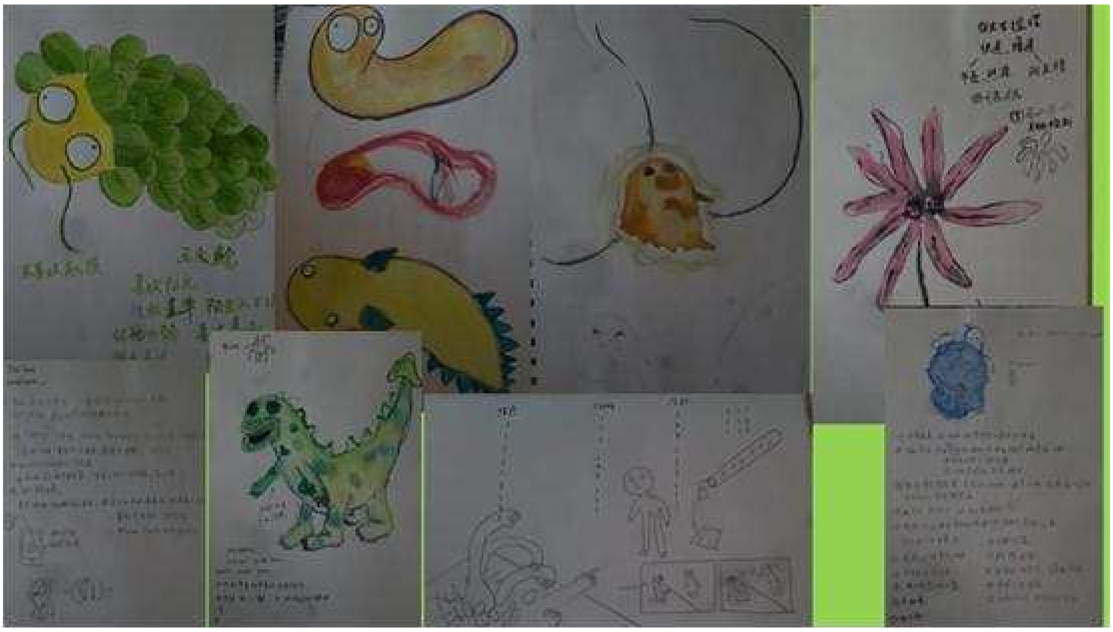

Figure 115 Minimal Robotic Animals and Fantastical Creatures

This page combines minimal design with imaginative speculation. The stick-like, three-degree-of-freedom forms show how extremely simple structures can still interact with humans—through bending, stretching, and swaying—while retaining a sense of life. Alongside these, the page presents diverse shapes such as leaf-like creatures, fish-like bodies, flower forms, and amorphous blobs. They do not replicate real animals but still convey presence and character. One figure, the yellow creature, is especially important: it was inspired by "a fart," something people usually find disgusting or repulsive. Here I explored whether such negative sensations can be reimagined into fantastical creatures, turning human disgust into a source of creative inspiration. This reflects not only the potential variety of robotic animal forms but also a deeper inquiry into human perception and cultural.

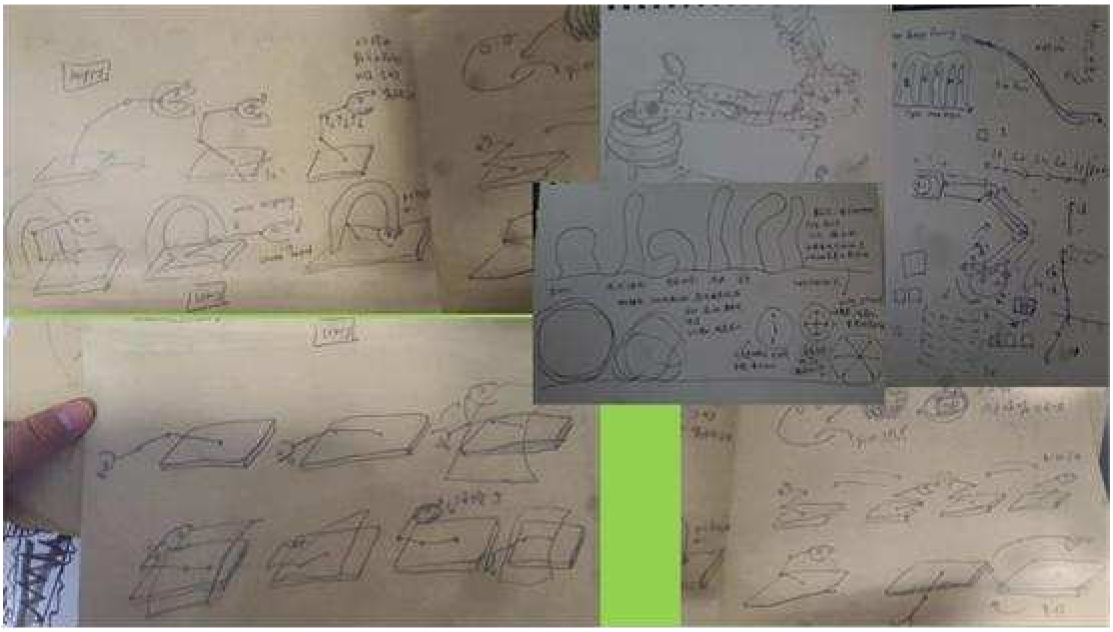

Figure 116 Sketches of Minimal Animal Motion Design

This page presents the earliest motion sketches for robotic animals, forming the basis of GUA's evolution from the first to the third generation. Using simple lines and geometric shapes, I broke down animal movements into minimal sequences such as head-lifting, stretching, bending, reaching, and retracting. These sketches show that very different forms—fish, tongues, tendrils—can all express "animalness" through similar motion logic. The notes also connect these movements to mechanical structures, exploring how to achieve lifelike dynamics with minimal joints and modules. From these simple sketches, the GUA's motion system took shape and gradually expanded in later iterations.

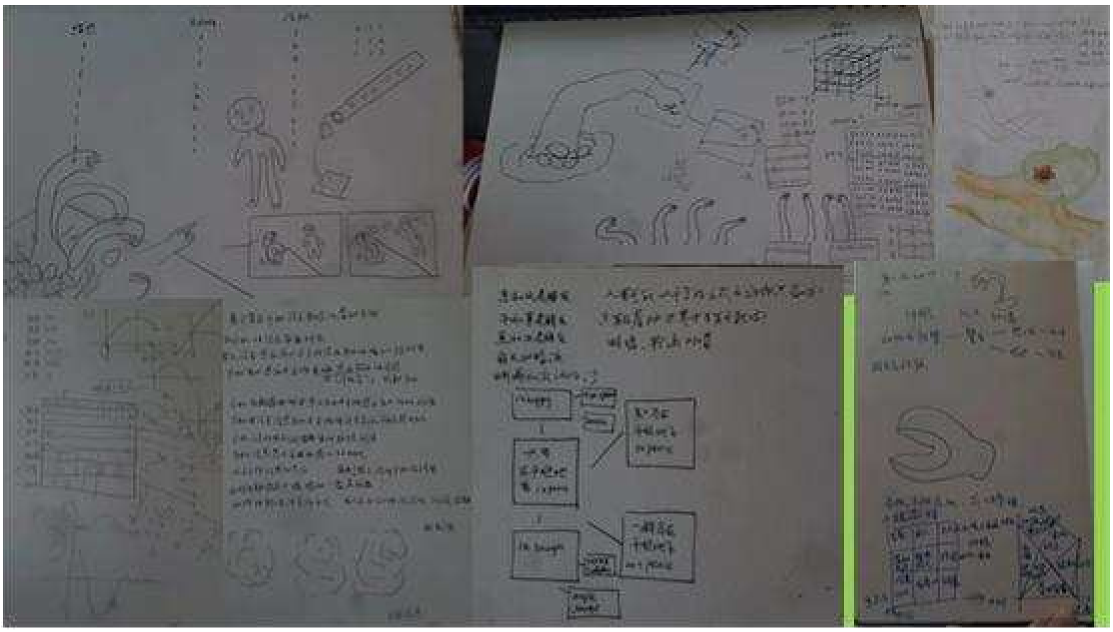

Figure 117 Parasitic Fantasy Creatures and Reflections on Animal Preference

This page imagines parasitic swarms as fantastical creatures: tiny, dense, invasive, associated with disease and fear. They embody disgust and discomfort, and by visualising such "negative factors," I was testing what makes robotic animals repulsive rather than appealing. Thinking through this contrast also clarified what humans actually prefer: animals that are larger, more autonomous, linked with health and joy, and often covered in fur—creatures that appear soft, expressive, and companionable. The notes at the bottom extend the emotion–activity–agency system with further tables and diagrams, refining how sensory input maps onto states and then onto behavioural libraries. In this way, the page combines an exploration of aversion with a continued effort to formalise behavioural design, showing that love and hate are two sides of the same coin in understanding human–animal attraction.

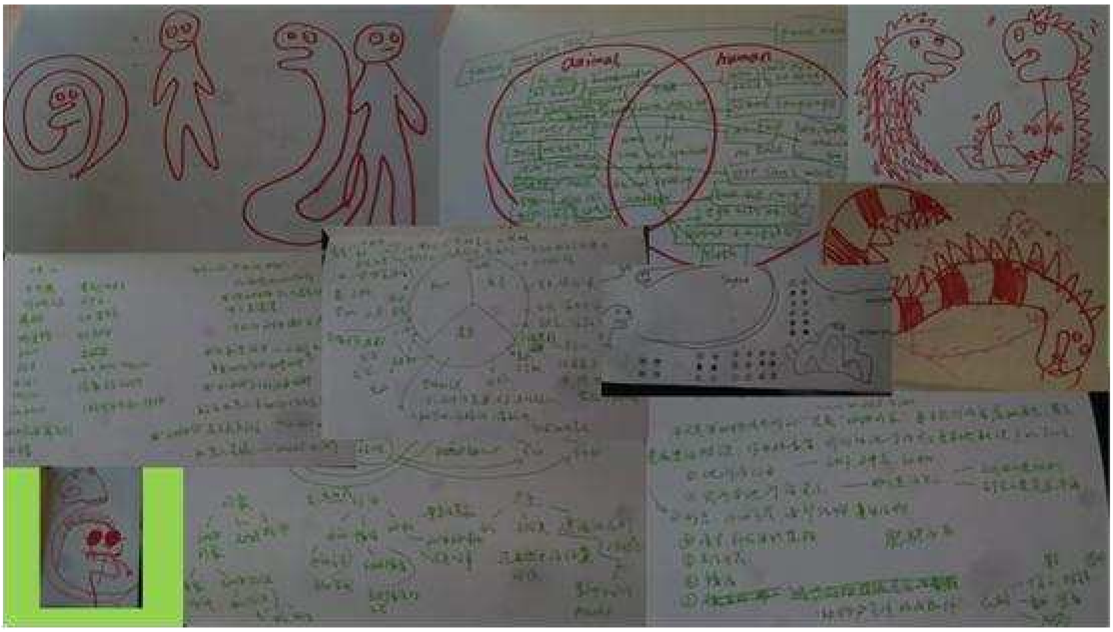

Figure 118 Concept board for a large, serpentine companion animal and GUA morphology keys

This page imagines a large serpentine companion—long, coiling, able to lean on the user or offer a light hug (never restraining), using posture to signal closeness, guidance and comfort. The side-by-side sketches show interaction poses (approach, head-lift cue, circling and returning), with quick notes on safe contact zones and pressure limits to avoid sensitive areas like the neck. The central animal–human Venn filters what to keep or drop: keep readable animal cues (ears/crest, tail, body arcs, lateral eyes, simple vocalisations), avoid human-style facial language; the aim is to stay with animal logic while remaining legible to people. Around it is a morphology kit: eyes (round/vertical slit/lateral), heads (horns, crest, mane), coat/skin (spiky vs fluffy, rings/dots), teeth (blunt/small fangs to reduce threat) and accessories (scarf, goggles, collar) to tune character and context. The ringed, segmented body suggests banded touch/pressure sensing; the small grids/dot arrays sketch sensor zoning and state mapping, which connect directly to my Emotion–Activity–Agency model to trigger chained behaviours like "approach → gentle touch → pause → step back." The extra studies (dragon/dino/caterpillar variants) test different skins on the same motion logic—as long as behaviour and silhouette language stay consistent, the form can vary while still reading as a soft, companionable animal.

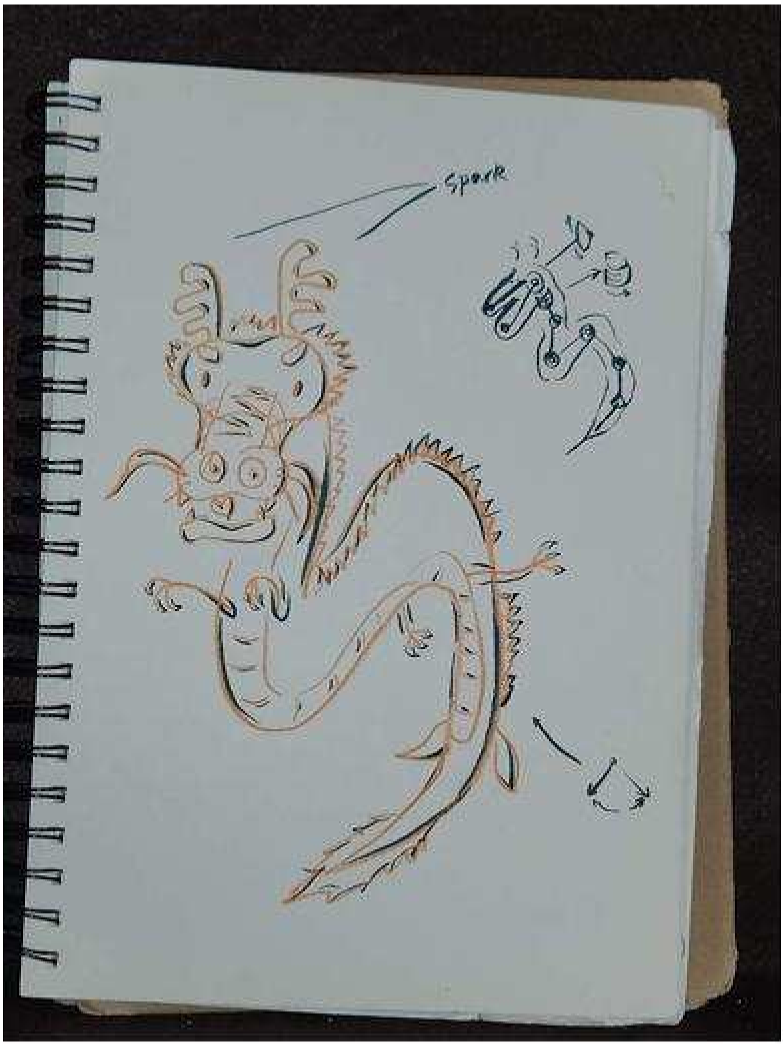

Figure 119 Sketch of a Dragon-Shaped Robotic Animal

This page sketches the idea of a dragon-shaped robotic animal. The main figure draws on the traditional Chinese dragon, with long body, whiskers, and antlers, expressing agility and symbolic presence. The dragon is not only a creature but a cultural emblem of power, protection, and spirit. Using it as a robotic animal form explores how technology can merge with cultural imagery. On the side, small mechanical sketches outline jointed limbs, claw-like parts, and rotatable modules, suggesting how such a fantastical form might be grounded in real mechanisms. The word “spark” points to the sense of energy and activation—imagining how mythical expression could be tied to robotic motion. This sketch shows that robotic animals need not be limited to lifelike companions; they can also embody myth and fantasy, expanding the design space into cultural and symbolic realms.

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