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A SHORT REVIEW ON ETHOLOGICAL BEHAVIOR MODELLING TECHNIQUES

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Abstract
Ethological behavior modeling techniques offer a structured framework for analyzing and comparing animal behaviors by identifying patterns within specific environmental contexts. These models have gained increasing prominence in robotics due to their potential to address challenges in human-machine interaction and enable autonomous systems to function effectively in complex, real-world settings. By mimicking animal responses to dynamic stimuli, ethologically inspired models enhance the adaptability and responsiveness of robotic systems. This paper reviews key ethological behavioral models, including those proposed by Tinbergen, Lorenz, and Gerard Baerends, with particular emphasis on two contemporary methodologies: knowledge-based ethologically influenced behavioral design and situated action-based behavior. These approaches highlight the importance of environmental adaptability and iterative refinement, illustrating the benefits of interdisciplinary collaboration between ethology and information sciences.

Keywords: *ethology, behavior modelling, knowledge-based ethologically influenced behavioral, design of situated action-based behaviour*

1. Introduction

Ethology, a specialized branch of zoology, focuses on the study of animal behavior in natural settings, emphasizing authentic interactions between organisms and their environments (Lorenz, 1981). Tinbergen's Four Questions framework addressing mechanism, development, evolution, and function offers a structured approach to behavioral analysis (Bateson et al., 2013). The mechanism dimension explores proximate causes such as neural activity underlying predation or hormonal changes influencing mating. Development examines how behavior emerges from the interplay of genetics and environmental influences across an individual's lifespan; for example, while bird migration is largely genetically encoded, lion cubs learn hunting strategies through social observation. The evolutionary dimension highlights how natural selection shapes adaptive behaviors, such as camouflage or cooperative hunting, to improve survival. The functional aspect considers the role of behaviors in survival and reproduction, exemplified by honeybee waggle dances or altruistic acts in meerkat societies (Von Frisch, 1974).

According to Drickamer (Drickamer et al., 1996), ethology examines how animals interact with their environments across physical, biological, and social dimensions. Physical responses include behaviors such as thermoregulation, burrowing, and migration. Biotic (biological) interactions involve predator-prey dynamics and courtship rituals. Social behaviors such as dominance hierarchies in primates or cooperative hunting strategies in wolves reflect evolutionary adaptations that promote group survival (Krebs et al., 2009; Slater, 1999).

Ethology also plays a critical role in applied domains such as conservation and technology. Behavioral research informs the development of wildlife corridors, species management plans, and strategies for mitigating human-wildlife conflict (Sutherland, 1998). In engineering, ethological principles have inspired biomimetic robotic systems, including robotic swarms modeled after ant colonies and drone algorithms influenced by predator–prey interactions (Siciliano et al., 2016; Hallam et al., 1992). Behavior-based robotics draws on ethological models to build adaptive systems using deliberative, reactive, or hybrid control architectures. For instance, warehouse robots optimize pathfinding, autonomous cleaning robots avoid obstacles, and self-driving cars integrate real-time sensing with pre-mapped navigation strategies (McFarland et al., 1993; Arkin, 1998; Breazeal, 2004).

The foundational contributions of Lorenz, Tinbergen, and von Frisch continue to shape modern ethology and its interdisciplinary applications. One notable concept introduced by Lorenz is that of fixed action patterns (FAPs) instinctive, species-specific behaviors triggered by particular stimuli. This idea has been adapted in robotics to develop systems capable of predictable yet flexible responses. For instance, security robots employ FAP-like algorithms to detect intrusions and initiate alert protocols. With the integration of computational modeling, these robotic systems are increasingly able to respond dynamically to environmental inputs, further demonstrating the lasting relevance of ethological theory in the field of robotic innovation (Schleidt et al., 2011).

This paper examines ethology and its interdisciplinary applications, with a particular emphasis on robotics. By enhancing the understanding of natural behavior, ethological frameworks contribute to the development of efficient, adaptive, and autonomous systems across both biological and artificial domains. When viewed through evolutionary and ecological perspectives, ethological modeling provides critical insights for the design of next-generation robotic systems and behaviorally informed technologies.

2. Ethological Behavioural Models

Drickamer and Vessey identified several key motivations for studying animal behavior, including scientific curiosity, a desire to understand interactions between animals and their environments, and the need to address pressing environmental challenges (Drickamer et al., 1986). These motivations highlight both the theoretical relevance and the practical value of analyzing how animals respond and adapt to dynamic ecological conditions. Ethology and robotics share compelling parallels, as both disciplines explore behavior generation, environmental interaction, and stimulus-response mechanisms. Influenced by foundational work from researchers such as Baerends, Tinbergen, and Lorenz, ethologists have moved beyond teleological interpretations of behavior, emphasizing instead the role of immediate stimuli and underlying biological mechanisms. These principles have profoundly shaped developments in robotics, where similar models are now used to create systems that simulate natural sensory perception, motion coordination, and autonomous navigation.

Roboticists have adopted ethological principles by designing artificial agents equipped with sensors, actuators, and behavior control architectures modeled after biological systems (Hallam et al., 1992; McFarland et al., 1993). This interdisciplinary synergy enables robotic platforms to mimic animal behaviors while serving as testbeds for validating ethological theories. As artificial systems reproduce natural behavioral patterns, engineers improve robotic design, and ethologists gain empirical insights into the mechanisms governing animal behavior. This reciprocal integration bridges ecological, technological, and conceptual domains-reinforcing the motivations originally outlined by Drickamer and Vessey.

Tinbergen Model: Tinbergen is a foundational figure in ethology, proposed a hierarchical model to explain the organization of animal behavior, drawing analogies to physiological systems such as respiration and digestion (Tinbergen, N., 2020). He argued that the nervous system organizes behavior through a layered structure, where simple motor actions are combined and coordinated into increasingly complex behavioral sequences. As illustrated in Figure 1 (Tinbergen, 1950), the model begins at the muscular level, where basic units of behavior such as leg movements or posture adjustments serve as the foundation. These elementary actions are then assembled into functional tasks (e.g., “go”), which are further integrated into goal-directed behaviors (e.g., “go + goal”). At the highest level, fully coordinated and context-sensitive actions emerge (e.g., “go + goal + action”).

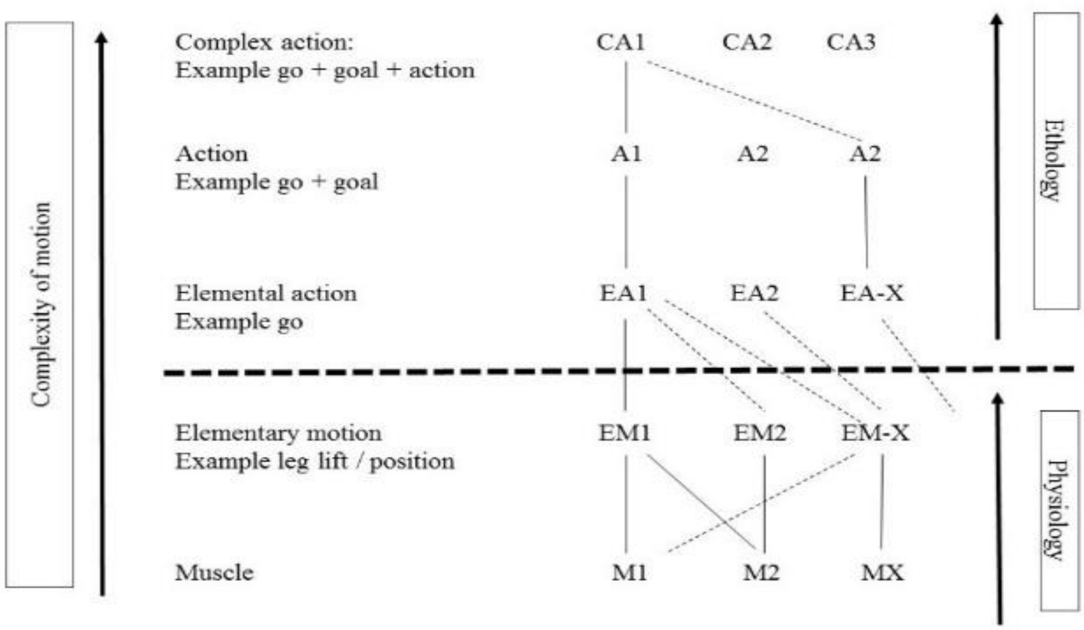

Figure 1. *Tinbergen hierarchy architecture (Tinbergen, 1950)*

Tinbergen emphasized the interplay between external stimuli such as visual cues from predators or ambient temperature and internal physiological states, including hormonal readiness and instinctual drives.

For instance, a male spiny fish may display territorial aggression or nesting behavior depending on environmental triggers (e.g., a rival male's presence) and internal hormonal states. The model illustrates how the nervous system integrates internal and external factors to generate coherent and adaptive behavioral responses.

This hierarchical perspective has had enduring influence beyond ethology, extending into fields such as neuroscience and robotics. In robotics, Tinbergen's model has inspired layered control architectures that organize robotic behavior into modular, stimulus-driven subsystems. These architectures support reactive and goal-oriented behaviors in autonomous agents, enabling them to navigate complex, dynamic environments with biologically inspired adaptability.

Konrad Lorenz Model: Lorenz is often regarded as the father of modern ethology, introduced the hydraulic model to conceptualize the interaction between internal motivation, external stimuli, and behavioral output. At the core of Lorenz's framework lies the concept of fixed action patterns (FAPs) stereotyped, species-specific behavioral sequences triggered by specific environmental cues. These innate responses are evolutionarily conserved and consistently observed across individuals of the same species, serving adaptive purposes (Lorenz, 1981).

Lorenz's hydraulic model, depicted in Figure 2 (Lorenz, 1950), uses a metaphorical reservoir system to illustrate motivational buildup. As time progresses, energy accumulates in the reservoir, representing an increasing internal drive for behaviors such as feeding, mating, or territorial aggression. Whether this "energy" is released depends on the presence and strength of a sign stimulus a key environmental cue. These stimuli act as weights on a balance mechanism, determining whether the innate releasing mechanism (IRM) conceptualized as a valve opens. When the valve is triggered, it releases the built-up energy, thereby initiating the corresponding fixed action pattern. This mechanism only activates when both conditions are satisfied: a sufficiently high internal drive and a suitable external trigger. For example, in certain fish species, a male's motivation for courtship builds hormonally over time. When a receptive female is present, her appearance acts as a powerful sign stimulus, prompting a predictable courtship display an archetypal FAP.

Lorenz's model underscores that behavior is neither purely reactive nor random. Instead, it emerges from a dynamic interplay between internal physiological states and external environmental conditions. While originally developed to explain animal instinct, the hydraulic model has exerted significant influence in neuroscience, psychology, and robotics. In artificial systems, it informs how motivation-like mechanisms and stimulus-response coupling can be engineered to create adaptive, context-sensitive robotic behavior. As a cornerstone of ethological theory, Lorenz's hydraulic model continues to provide essential insights into the structured organization of instinctual behavior in both biological organisms and autonomous artificial agents.

Gerard Baerends Model: Baerends behavioral model presents a comprehensive and structured framework for understanding how animals organize and prioritize behaviors over time and across environmental contexts. Particularly influential in studies of avian behavior, the model emphasizes the temporal and contextual dynamics of behavior regulation, as demonstrated in the nesting behavior of herring gulls (Baerends, 1970; Baerends et al., 1970), as shown in Figure 3. It focuses on how distinct behavioral systems interact, suppress one another, and dominate in response to an animal's immediate ecological demands. This regulatory approach ensures that animals engage in the most contextually appropriate action at any given time.

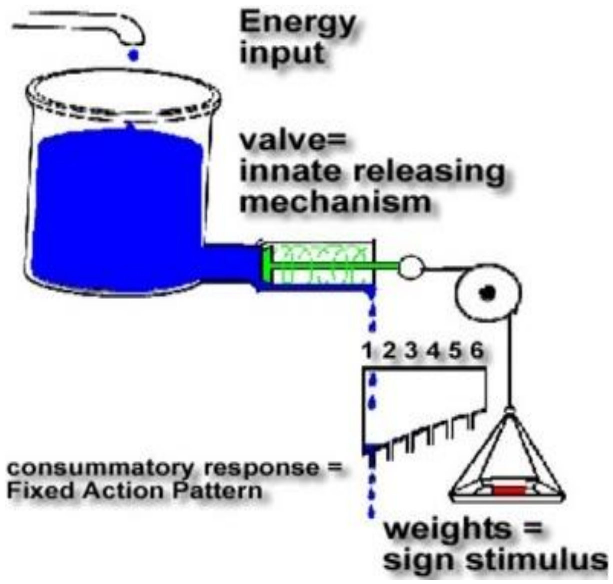

Figure 2. *Lorenz Hydraulic Model (*Lorenz*, 1950).*

Baerends identifies three core behavioral systems: Nesting/Incubation (N), Escape (E), and Preening (P). These systems are functionally interlinked but mutually inhibitory, meaning that only one system can dominate at a time. The Nesting system governs activities such as incubating eggs, retrieving displaced eggs, and modifying nest structure. The Escape system triggers flight or locomotion in response to potential threats, while the Preening system oversees grooming behaviors and feather maintenance. During incubation, for instance, nesting behaviors typically take precedence suppressing escape or preening unless disrupted by a salient external cue such as a predator.

Central to Baerends model is a feedback-based control loop that regulates behavioral decision-making. The loop comprises several interconnected components: Input Processes (IP) that gather both external stimuli and internal physiological states; the Expected Clutch Stimulus (EC), representing an idealized goal such as a complete egg clutch; Feedback (FB), which conveys the current state of the nest; the Comparison Unit (CU) that identifies discrepancies between actual and expected conditions; and the Integration Unit (I) that processes these inputs to determine the next appropriate action. If, for example, feedback reveals a missing egg, the Nesting system becomes dominant and initiates a Fixed Action Pattern (FAP), such as retrieving the egg. FAPs are central to Baerends framework. These are species-specific, stereotyped behavioral responses that are reliably activated under suitable conditions. Nesting FAPs include activities like shifting or adjusting nesting material; Escape FAPs involve rapid locomotor actions such as flight; and Preening FAPs relate to feather realignment and personal maintenance. Importantly, these FAPs are activated only when their associated behavioral system is in control, ensuring that behaviors are executed appropriately and without conflict.

Baerends model demonstrates a dynamic and modular organization of behavior, allowing animals to switch efficiently between tasks in response to environmental fluctuations. For example, when a predator appears near a herring gull's nest, the Escape system temporarily overrides the ongoing nesting behavior. Once the threat disappears, the Nesting system regains control, and incubation resumes. Likewise, Preening behaviors emerge during moments of safety or inactivity, reflecting a shift in system dominance.

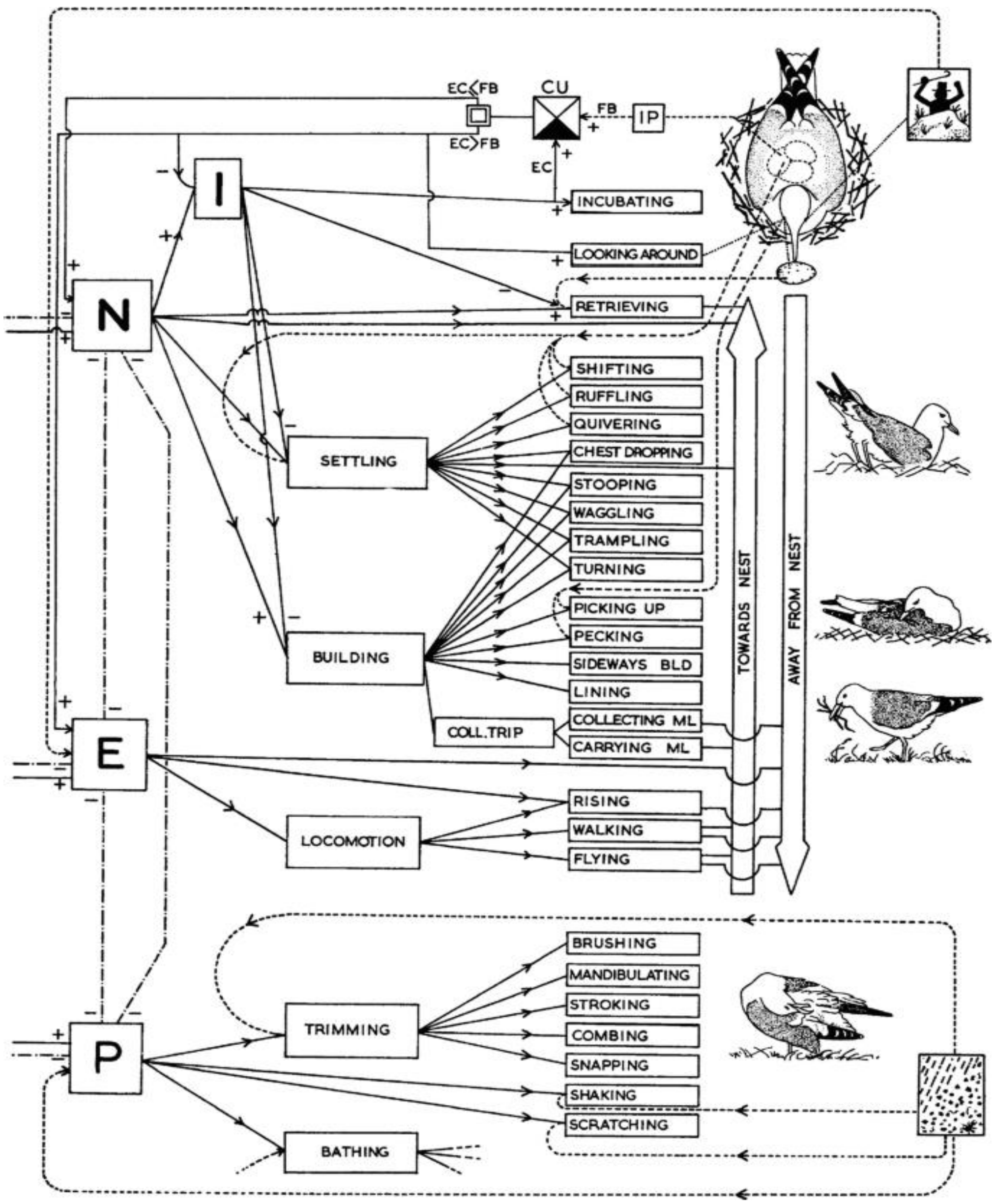

***Figure 3**. Baerends model of herring gulls nesting behavior (Baerends et al., 1970).*

This real-time adaptability mirrors biological intelligence and survival strategies. Overall, the Baerends contribution to ethology lies in his systematic integration of hierarchical behavioral systems and real-time feedback mechanisms. By providing a model that accounts for both environmental triggers and internal regulatory processes, his work offers a nuanced explanation of animal behavior under natural conditions. The model has had significant implications not only for ethological theory but also for fields such as robotics and artificial intelligence, where its structure has inspired adaptive behavior selection architectures in autonomous agents. It exemplifies how biological principles can be abstracted into control models capable of guiding behavior in both living organisms and engineered systems.

Limitations of Models: While classical ethological models such as Tinbergen, Lorenz, and Baerends have greatly informed behavior-based robotics, they are not without limitations in modern applications. These models primarily emphasize instinctive, species-specific behaviors and often lack mechanisms for real-time learning or adaptation to novel stimuli. For instance, Lorenz's hydraulic model assumes behavior is triggered only when motivational thresholds and stimuli align, which may not accommodate the dynamic sensory environments robots operate in. Similarly, Tinbergen's hierarchical structure provides limited flexibility for context switching in unpredictable scenarios. Baerends' mutually suppressive systems, while effective in constrained biological contexts, may struggle in robotic systems that require concurrent task execution or continuous multi-objective prioritization. Furthermore, these models generally overlook the role of social learning, memory, and reinforcement factors increasingly relevant in robotics. Recognizing these limitations is crucial for advancing hybrid approaches that combine ethological inspiration with adaptive algorithms and learning-based control architectures.

3. Methodology

Behavior modeling methodologies provide structured frameworks for analyzing, simulating, and predicting behavioral patterns across disciplines such as ethology, psychology, robotics, and artificial intelligence. These approaches aim to uncover how behavior emerges through the interplay of internal motivations, external stimuli, and environmental conditions. Recent advances have combined biological insights with computational tools, enabling researchers to study behavior in both natural and artificial systems more effectively. Among the earliest and most influential approaches, ethological models focus on innate behaviors and their hierarchical organization. Pioneers such as Nikolaas Tinbergen and Konrad Lorenz introduced foundational concepts like fixed action patterns (FAPs) stereotyped, species-specific behaviors triggered by specific cues. Tinbergen's hierarchical model demonstrates how simple motor actions are assembled into complex behavioral sequences governed by motivational states and environmental inputs. In contrast, Lorenz's hydraulic model conceptualizes motivation as an accumulating internal force that is released upon encountering an appropriate external stimulus. These classical frameworks have profoundly influenced behavior-based robotics, where similar mechanisms now guide robot responses in dynamic environments.

In addition, behavioral ecology models adopt an evolutionary lens to examine how behaviors contribute to survival and reproductive fitness in ecological contexts. For example, optimal foraging theory explains how animals maximize energy efficiency, while game theory models address strategic behaviors such as competition, cooperation, and conflict. These frameworks reveal the adaptive value of behavioral strategies shaped by natural selection, offering insights that extend to artificial systems. Building upon these biological foundations, robotics and artificial intelligence have integrated behavior modeling to create adaptive and autonomous machines. In behavior-based robotics, complex tasks are decomposed into simpler, reactive modules inspired by natural behavior. Notably, Rodney Brooks' subsumption architecture structures robotic control hierarchically enabling robots to perform layered tasks from navigation to goal-directed action (Brooks, 2003). Hybrid models, which integrate behavioral logic with computational techniques such as reinforcement learning, further enhance adaptability by allowing robots to evolve their behaviors based on feedback and environmental interaction (Brooks, 1986).

Together, these methodologies form a continuum spanning classical ethological theory to modern AI-driven robotics. Each provides a unique lens for modeling behavior whether in animals or machines. As these approaches continue to evolve, they deepen our understanding of behavioral complexity and push the boundaries of intelligent system design. The following section introduces two key methodologies Knowledge-Based Ethologically Influenced Behavioral Design and Situated Action-Based Behavior that address contemporary challenges in robotic behavior modeling by integrating biological realism with engineering innovation.

Knowledge-Based Ethologically Influenced Behavioral Design*:* It is an interdisciplinary methodology that integrates principles from ethology the scientific study of animal behavior into the development of adaptive robotic systems. By analyzing how animals respond to external stimuli, researchers extract behavioral models that guide the creation of biologically inspired robotic actions. These models serve as foundational blueprints for designing efficient, robust, and responsive robots, while also providing valuable feedback to ethological science. The methodology follows a structured, iterative process, as illustrated in Figure 4. It begins with a comprehensive review of ethological literature to identify relevant behavioral patterns, triggering mechanisms, and environmental interactions. Based on this analysis, a behavioral model is formulated and implemented within the robotic platform. The model is then customized to match the robot's sensorimotor architecture, ensuring that the system can replicate target behaviors using its specific hardware and software components.

To assess the model's validity, robotic experiments are conducted across a range of environmental conditions (Lone et al., 2024). These trials yield empirical data used to evaluate the model's performance and its fidelity to the biological behavior it seeks to emulate. Discrepancies or performance deviations are analyzed, prompting iterative refinements in the model's structure and implementation. This calibration process enhances both behavioral accuracy and the system's functional reliability. A key innovation in this methodology is its bidirectional feedback loop. Insights from robotic testing frequently expose limitations or missing variables in the original biological models, thereby inspiring new directions in ethological research. For instance, unexpected robot behavior may suggest unaccounted environmental triggers or thresholds in animal behavior, encouraging further observation or experimental studies. This dynamic feedback cycle continues until the robotic system closely approximates the target biological behavior.

The implications of this methodology are substantial. In robotics, it supports the creation of autonomous systems that exhibit adaptability, efficiency, and resilience characteristics of natural organisms. Such robots can effectively operate in complex, unstructured environments, engage in human–robot interactions, and adjust their behavior in real time. In the field of biology, testing animal behavior through robotic implementation provides an experimental complement to traditional observation-based research. Ultimately, knowledge-based ethologically influenced behavioral design exemplifies the productive synergy between ethology and robotics. By iteratively translating biological insights into robotic functionalities and refining models through empirical testing, this approach fosters technological innovation while deepening scientific understanding. It stands as a scalable and interdisciplinary framework for the development of intelligent, behaviorally grounded autonomous systems.

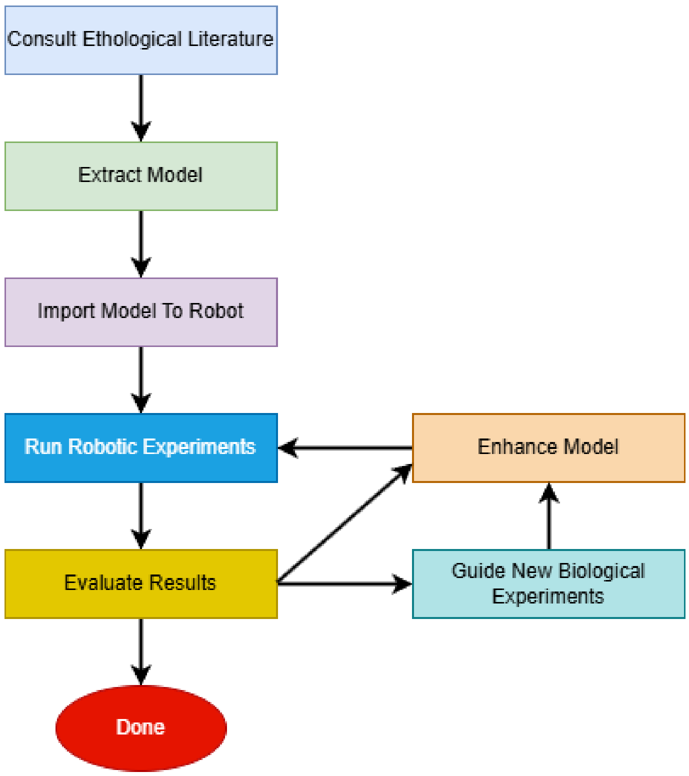

Figure 4. *A knowledge-based ethological approach to robot behavior design.*

Design of Situated Action-Based Behavior*:* This model emphasizes the development of robotic systems capable of dynamically adapting to environmental and situational contexts. Unlike traditional robotic paradigms that rely on rigid, pre-programmed decision-making, this approach prioritizes real-time interaction with the robot's surroundings. By continuously interpreting external stimuli, robots are empowered to autonomously choose context-appropriate actions, enabling them to navigate and respond effectively within complex and unpredictable environments. Rooted in principles of animal behavior, this design methodology enhances both adaptability and operational robustness (Lone et al., 2024).

The design process begins with a thorough evaluation of the robot's operational environment, as illustrated in Figure 5. Analyze potential scenarios, environmental challenges, and relevant external stimuli that the robot may encounter. These elements are organized into distinct situational categories, simplifying environmental complexity by clustering similar conditions. For each defined situation, specific behavioral responses are developed, often inspired by ethological observations of animals reacting to analogous stimuli.

The emphasis is placed on external interaction such as navigation, obstacle avoidance, and object manipulation rather than solely on internal computational processes, thus ensuring high relevance to real-world functionality.

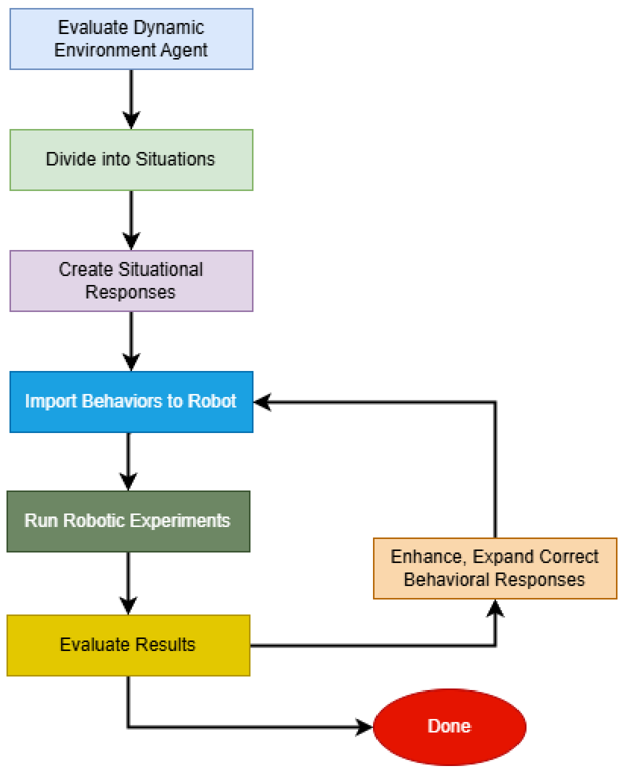

Figure 5. *Design procedure for Situated Action-Based Design.*

Once the situational responses are developed, they are encoded within the robot's control architecture. The robot is then equipped to perform these behaviors using its sensorimotor systems. The design also includes mechanisms to enable smooth transitions between behavioral states, allowing the robot to shift seamlessly from one situational response to another based on changing environmental inputs. This transition capability is vital for maintaining consistent and adaptive behavior during operation. Following implementation, the system undergoes rigorous testing in both real-world and simulated environments. These experimental trials are used to evaluate the consistency, reliability, and context-responsiveness of the programmed behaviors. Performance data and observational feedback are analyzed to identify any deficiencies or mismatches between expected and actual responses. Behavioral modules are refined through an iterative improvement process until the robot demonstrates reliable, stable, and efficient behavior across a broad range of situations. A defining feature of this methodology is its environmentally grounded behavior selection. Robots determine actions based on external conditions and the expected consequences of those actions, closely emulating the decision-making processes observed in animals. Furthermore, the methodology employs hierarchical behavioral architecture, facilitating organized control and fluid transitions between behaviors, which enhances the robot's responsiveness in complex operational domains.

Situated action-based behavior design is highly applicable in domains requiring real-time responsiveness and environmental sensitivity. In autonomous navigation, for instance, this approach allows robots to function in unpredictable terrains such as disaster zones or rural landscapes. In social robotics, it supports nuanced human-robot interaction in healthcare and service contexts. Similarly, in environmental monitoring, this model enables robotic agents to perform tasks effectively in variable and challenging ecosystems such as agricultural fields, forests, and underwater habitats. In conclusion, situated action-based behavior design represents a critical advancement in the field of robotics. By mirroring the adaptability of animal behavior and refining actions through continuous experimentation, this methodology empowers robots to operate autonomously in complex, real-world environments. Its focus on interaction, behavioral flexibility, and hierarchical structure positions it as a foundational strategy in the development of intelligent robotic systems.

4. Conclusion

Ethological principles have significantly influenced robotics by modeling animal behaviors to tackle complex, real-world tasks such as using nesting behaviors in birds or interaction patterns in fish to inform robotic task execution. These biologically inspired strategies not only enhance the adaptability and autonomy of robotic systems but also provide ethologists with practical tools to test and refine behavioral theories through implementation. Behavior modeling methodologies, particularly knowledge-based and situated action-based designs, serve as effective bridges between biology and technology. By emphasizing environmental responsiveness and iterative refinement, these approaches integrate naturalistic behavior into artificial systems. This interdisciplinary synergy advances innovation in robotics while simultaneously enriching behavioral science. Therefore, the reciprocal relationship between ethology and robotics underscores the transformative potential of cross-disciplinary collaboration, fostering sustained progress and deeper understanding across both fields.

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