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**The Impact of Biomimetic Robots on Animal Behavior –
Analysis of Experimental Research Based on the Use of the
Mobile Robotic Rat WR-5**

This paper has been translated from the original language (Polish) with the use of ChatGPT 4o and edited by the author.

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Abstract

The aim of the thesis is to analyze research on animals using biomimetic robots, focusing on the robotic rat WR-5 and the interactions that the robot can establish with living organisms.

In the first chapter, *Theoretical Frames for Biomimetic Robot Interaction with Animals*, I discuss the basic mechanisms of biomimetic robots and attempt to describe their cognitive functions in a general manner. The next chapter, titled *Characteristics of the WR-5 Robot*, provides a description of technical parameters and presents the development of the robotic rat WR-5. This chapter also includes a description of the work on creating subsequent versions of the robot, considering the technical progress of the Waseda Rat. Chapter three, *Research and Evaluation of the WR-5 Robot Interaction with Rats*, discusses the social interactions of the robot, using studies in which WR-5 was tasked with inducing depression in rats. In this chapter, I also conduct a preliminary analysis of the results presented in the above-mentioned studies. The conclusion includes a summary and interpretation of the experiments presented in the thesis. Finally, I present the advantages and disadvantages of robot-animal interactions, taking into account the ethical aspects of research on animals using biomimetic robots. The conclusion also outlines the prospects for the development of biomimetic robot interactions with animals.

The methodology involves the reconstruction and interpretation of scientific works, with a particular focus on the research of Qing Shi, a Chinese scientist specializing in biomimetic robotics at the Institute of Technology at the University of Beijing.

The choice of the research topic stems from the desire to delve deeper into the subject of biomimetic robot interactions with animals. I believe that the thesis can be important in terms of compiling available materials on the topic of the Waseda Rat in one article. I also hope that this work will contribute, at least to some extent, to further developments in robotic biomimicry in a more animal-friendly manner. One of the motivations for writing the thesis is the need to illustrate the issues arising from the interaction of animals with artificial intelligence. I aim to demonstrate that, in not every case, experiments involving animals are a good solution and that technological progress allows scientists to treat laboratory animals more humanely.

Introduction

In the course of natural selection, certain animals have achieved a high level of functioning. Numerous detailed observations and neuronal studies of animals indicate that representatives of many species exhibit diverse exploratory-cognitive abilities, and consequently, a certain level of consciousness. Vertebrates, due to an evolutionary process similar to humans, possess neurological structures similar to the human brain, and can thus be considered beings that are evidently conscious. Intelligence, the capacity for sensation, and consciousness are essential criteria in considering the ethical significance of vertebrates. Invertebrates, although significantly different from humans, can also exhibit intelligent behaviors. For instance, the octopus is generally regarded as an intelligent creature and should be treated according to the ethical norms (Singer, P., Tse, Y.F., 2022).

The ethical standards of animal research constitute a crucial aspect in this work, given that its primary focus is on the investigation of interactions between laboratory animals and robots. In 2006, the National Ethics Committee for Animal Experimentation in Poland issued a resolution outlining the degrees of intervention in an animal's organism during experiments involving laboratory animals, in accordance with EU requirements. The scale is five-tiered, with the key aspects of each level briefly described below.

1. Non-invasive procedures - encompassing observations and behavioral tests in which animals are not exposed to stress or any harm to their health.
2. Procedures causing mild and transient stress or pain, or prolonged but mild discomfort - temporary immobilization for clinical examination, such as blood sampling or injection. Euthanasia by standard methods is permissible or experiments under deep anesthesia.
3. Procedures leading to short-term and moderate stress or pain - involving minor interventions or exposure to stress-inducing stimuli, with the provision of escape opportunities for the animals. Procedures should not significantly impact the behavior of animals, leading to increased motor activity, aggression, or a desire for isolation from other individuals.
4. Procedures causing severe pain or stress, leading to permanent damage to the body or psychological functions - serious surgical procedures, changes

significantly affecting the proper functioning of the organism, exposure to harmful or highly stressful stimuli without the possibility of escape. This category also includes any research leading to severe mental disorders or changes in the sensory-motor organization of the animal.

5. Procedures causing extreme suffering - considered as the absence of anesthesia, euthanasia in a manner other than recommended by the National Ethics Committee, inducing severe changes in the body, improper housing significantly affecting the health of animals.

Based on the invasiveness scale, local ethics committees provide opinions to research institutes (Smaga, Ł., 2010, pp. 180-182).

Environmental adaptation of animals and their adaptive abilities have created opportunities for the development of a new scientific field – biomimetic robotics. Biomimetics is based on the imitation of biological systems in technology, whereby biomimetic robots are biologically inspired and aim to accurately replicate the strategies, principles, and mechanisms of living organisms. Technological advancements and progress in research on living organisms enable biomimetic robots to mimic animal behaviors. Their mobile capabilities, coupled with self-regulation functions, allow new biomimetic robots to closely interact with living organisms and study their behaviors. By emulating the characteristics and functions of animals, robotic systems aim to achieve similar adaptive abilities, efficiency, and flexibility.

Biologically inspired robots are easy to maintain, and their behaviors are relatively easy to manipulate. Upon reaching an appropriate level of advancement, these robots can potentially replace live animals in research, providing scientists with significantly broader possibilities, and in the longer term, proving to be more cost-effective (Gao, Z. et al., 2019, p. 340).

Due to the rapidly advancing field of biomimetic robotics, scientists are gaining increasing knowledge about various animal species. Biomimetic robots are often placed in groups of animals to study their behaviors. Halloy and others conducted research on decision-making processes in animal groups. Using an autonomous robotic cockroach, scientists investigated a group of cockroaches and discovered that in a controlled environment, cockroaches make decisions about the direction of escape based on a quorum principle. In the case of cockroaches, there is a mechanism of communication through pheromones, which are chemical substances released by individuals that can influence the behavior of other cockroaches. Through pheromone interactions,

cockroaches can coordinate their actions and make decisions collectively (Chandrasekaran, S., Hougen, D., 2006).

Research on decision-making processes in fish has been conducted using a remotely controlled robotic fish placed in a maze with a Y-shaped configuration. It was found that fish, similar to cockroaches, make collective decisions through a voting mechanism. Decisions are based on interactions among individual members within the school. Fish communicate with each other using various signals such as body movements, color changes, or emitted sounds, allowing the biomimetic robot to gather information. Data collected by biomimetic robots studying group behaviors of animals are crucial, as they can help verify hypotheses put forward by scientists. For example, thanks to an interactive robotic fish, scientists discovered that the topological model of collective fish shoal behavior is more realistic than the metric model¹ (Halloy, J. et al., 2007).

Biomimetic robots can engage in interactions with animals, monitor their behavior, and collect data. Exposure to the functioning of living organisms positively influences the improvement of robots that learn to interact with animals. The learning mechanisms in such robots allow scientists to more accurately model animal behaviors. There are already biomimetic robots utilizing mechanisms inspired by the vision of bees to navigate obstacles. Additionally, there are robotic crickets that can locate a female by tracking the sounds she produces. Robotic lobsters, capable of tracking chemical pollutants to their source, and a group of robotic ants that can construct an anthill, are also examples of the diverse applications of biomimetic robotics.

Numerous studies employing biomimetic robots have been conducted on rats. These animals are frequently utilized in laboratory research due to their high intelligence and social capabilities. Rats are relatively easy to maintain and reproduce, making them ideal candidates for studies. Research has shown that robotic rats can influence live rats, for instance, by exhibiting aggressive behavior towards the studied rats or persistently following one rat, inducing stress in the pursued rodent. However, the locomotion mechanisms of robotic rats are not yet natural enough for them to

¹ The metric model defines the distance between elements of a set (in this case, fish) and assumes that elements closer to each other have stronger interactions. This model does not illustrate the density of the set, making it not the best way to model the movement of a shoal of fish. Topological modeling, on the other hand, is more general and defines the relationship between elements of the set, regardless of the distance between them. Consequently, the interaction among fish in a shoal will depend on the density of the shoal, not the distance between them (Ballerini, M. et al. 2008).

function normally among live rats. This is associated with the limited mobility of the bionic spine and insufficient levels of degrees of freedom² (Gao, Z. et al., 2022, p. 223).

Knowledge about animal behaviors gained through research using biomimetic robots can enhance the functionality of these robots. Biological mechanisms can serve as examples for the potential development of biomimetic robotics because years of evolution have brought living organisms to a level of sophistication that technology has not yet reached. Scientists, by drawing inspiration from biological mechanisms, can improve the performance of robots. This creates a mutual benefit where insights from the natural world contribute to advancements in robotic technology, and concurrently, the development of biomimetic robots provides a platform for a deeper understanding of biological systems (Webb, B., 2000, p. 545).

² Degrees of Freedom (DOF) refer to the concept defining the number of independent ways a robot can move. The number of degrees of freedom determines the directions in which different parts of the robot can move. A robot with a higher number of degrees of freedom is more flexible and capable of performing complex tasks, but this comes with challenges in controlling of the robot and increased energy requirements for the mechanism (Lewis, F.L., Dawson, D.M., Abdallah, C.T., 2003, s. 4-9).

Chapter 1

Theoretical Frames for Biomimetic Robot Interaction with Animals

Biomimetic robotics had its origins seventy years ago. The pioneering work in biomimetic robots can be attributed to Grey Walter, a British neurologist and biologist from Bristol, who, in the 1950s, published the article *An Imitation of Life*, presenting two robotic turtles as the first examples of biomimetic robots. These were simple mechanisms that reacted to touch and moved towards light. However, uniform and weak illumination was not a sufficient stimulus to activate the movement of these turtles. They responded, however, to distinct light reflexes or changes in illumination. In the absence of access to light, the robots continuously traversed the available space, altering their trajectory upon encountering an obstacle they could not move (Walter, G., 1950).

The first robots, that closely fall within the category of biomimetics, emerged many years ago. One of the earlier examples is a robot named “Wabot-1”, developed in the 1970s by Japanese scientist Ichiro Kato. This robot drew inspiration from human movement and aimed to replicate human motor abilities. Wabot-1 featured electromechanical systems that mimicked human limbs, enabling it to move (Serafini, P. et al., 1974). Another early achievement in biomimetics is the robot named “Sprawlita”, inspired by the locomotion of beetles. It was designed in the 1990s by scientists from the University of Berkeley in California. “Sprawlita” had six legs and could traverse uneven terrain, imitating the gait of beetles (Cham, J.G. et al., 2002). Another example is the robot called “RoboPike”, designed to mimic the movement and behavior of a pike fish. The robot investigated the biomechanics and dynamics of fish movement to better understand its swimming capabilities (Morgansen, K.A. et al., 2001).

1.1 The movement mechanisms in biomimetic robots

The way animals move serves as a significant inspiration for scientists designing biomimetic robots. Through evolution, many organisms have developed motor mechanisms that greatly leverage the principles of physics. Translating these biological mechanisms into technical ones has allowed creators of biomimetic robots to employ state-of-the-art locomotion technologies. Solutions such as walking, climbing, jumping, crawling, and flying have been implemented in biomimetic robots, which are briefly outlined below.

I. Legs Movement – robots can have virtually any number of legs. Robots with four limbs are typically programmed using three mechanical structuring methods: serial structure, parallel structure, or hybrid structure. In a serial structure, each leg of the robot is powered by separate motors and axes, and its movement is independently controlled. This allows for greater precision and control of the trajectory of movement, often requiring a higher number of motors and a more complex mechanism. In a parallel structure, each leg of the robot is attached to a central point, and the leg movements are controlled by mechanisms composed of several linkages driven by common motors. Such a mechanism is challenging to control but provides greater endurance and stability for the robot. As the name suggests, a hybrid structure combines elements of both previous structures. Depending on the specific design, each leg of the robot may have separate drive axes or shared motors and mechanisms controlling leg movements. This results in greater flexibility in design, achieving a balance between precision and durability.

Serial structure is an open mechanism that assumes a four-part spatial mechanism or a four-part planar mechanism. The four-part spatial mechanism consists of four interconnected levers that move in three dimensions. This mechanism is applied in various devices such as industrial robots, as well as in medical and biomechanical applications. On the other hand, the four-part planar mechanism consists of four interconnected levers that move only in one plane. It is widely used in various applications, including hinges in doors or windows and clock mechanisms (Miller, S., 1996, pp. 29-34). The serial structure, for instance, was utilized by scientists at the Massachusetts Institute of Technology in USA, who built the Mini Cheetah robot, which moves on four legs (Carlo, B., Katz, B., Kim, S., 2019)³. Parallel structure is a closed system that consumes a small amount of energy and allows for high precision. On the other hand, hybrid structure combines serial and parallel structures, enabling the robot to move quickly and stably. Kinematic analysis and simulation have shown that designing the movement of biomimetic robots in this way is highly effective.

³ The Mini Cheetah robot gained popularity by appearing on the American television programme “The Tonight Show” hosted by Jimmy Fallon. In the show, the robot showcased its capabilities, including running, jumping, and flipping in the air. This encounter contributed to increased interest and recognition of quadrupedal robots (author's note).

Hexapod robots with six legs are typically designed using a series joint type. The series joint type refers to the construction of a robotic joint where rotations occur successively along a series of interconnected links. These links are connected by joints that allow movement relative to each other. An example of a series joint structure is the human arm, where rotations occur successively in the shoulder, forearm, and hand. This type of joint structure is employed in robots where the movements of individual limbs depend on the positions of the other limbs. Typically, each leg consists of a base, mechanical shin, and femur bones, and their degree of freedom is at the first level (Zielińska T., 2003, pp. 37-47).

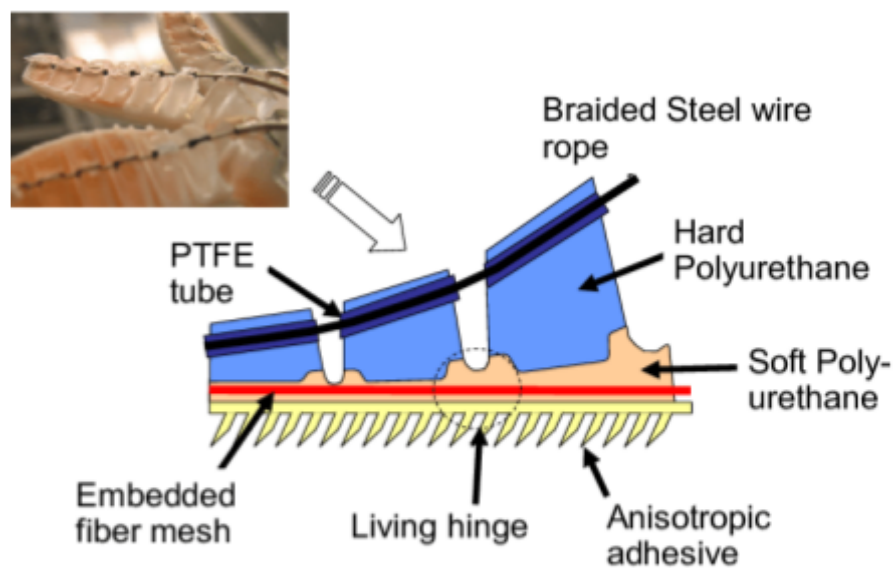
Step planning is foundational in the research of multi-limbed robots as it encompasses the trajectory of motion, calculation of the anticipated limb placement, and the planning of limb and joint mobility. Planning the timing of limb movement influences the final motor outcome of the biomimetic robot. This enables the full utilization of the potential of the employed mechanism and allows the robot to navigate through complex environments. During movement on flat terrain, steps are periodic and rhythmic. On uneven surfaces, however, limb movement is elongated, resembling the biological movement of an animal in an unfamiliar or challenging environment, with stabilization adapted to external conditions.

II. II. Climbing – in biology, climbing mechanisms are highly developed in many organisms. Geckos climb using van der Waals forces⁴. Geckos possess special structures on their paws, called lamellae, which enable them to utilize these forces to adhere to surfaces. The lamellae on gecko paws consist of thousands of microscopic hairs, called setae, each of which further divides into even smaller structures known as spatulas (*spatulae*). Spatulas are so tiny that they interact with surface molecules and leverage van der Waals forces to maintain adherence. Thanks to this structure, a gecko can establish hundreds of thousands of contacts with a surface, providing strong adhesion even on smooth and vertical surfaces (Przestalski, S., Hładyszowski, J., 2003, pp. 139-140).

Insects, on the other hand, use tiny spines on their feet to ensure grip, while animals such as rats or cats employ claws for this purpose.

⁴ Van der Waals forces consist of orientational, inductive, and dispersive forces that collectively induce the mutual attraction of electrically neutral charges. Van der Waals forces are weak interaction forces between molecules, resulting from momentary electron polarization (Przestalski, S., Hładyszowski, J., 2003, p. 139-140).

The third-generation Stickybot, designed by Mark Cutkosky, a professor of mechanical engineering at Stanford University in California, was created based on the mechanisms of a gecko's functioning, characterized by excellent body adhesion to surfaces. Biologically inspired by the gecko's functioning, the robot can move on vertical, slippery surfaces, and in similarly challenging environments. The authors described the adhesion system for the robot climbing vertical surfaces using pads equipped with adhesors⁵ that enable surface adhesion. This system relies on hierarchical, directional, and distributed control of adhesion forces. The notion of hierarchy refers to the ability to change the method of adhesion to the surface as needed, while directionality and distributed control indicate that the robot can regulate the direction of movement and is equipped with multiple individually controlled adhesors. The mechanical schematic of Stickybot's paw is presented in the illustration below (Kim, S. et al., 2007).



Img. 1 Mechanical Diagram of Stickybot's Paw
 Kim, S. et al. (2007) *Whole body adhesion: Hierarchical, directional and distributed control of adhesive forces for a climbing robot*, w: *IEEE International Conference on Robotics and Automation*, p. 1269.

PTFE tube is made from Teflon, a material highly resistant to chemical and thermal influences. It is used as a component in the construction of Stickybot's paw, providing

⁵ The term 'adhesor' refers to devices, materials, or structures that enable attachment to a surface through adhesion. Adhesion refers to the phenomenon of two surfaces sticking together, which can be caused by chemical or physical forces (Kim, S. et al., 2007).

durability and resistance to various environmental conditions. Anisotropic adhesive substance is a material that exhibits different adhesion strengths depending on the direction of force application. In the case of adhesors, anisotropic adhesive substance can assist in achieving better adhesion to surfaces by employing various structures or microscopic arrangements on the adhesor's surface, allowing for control over the direction and intensity of adhesion. Consequently, the adhesor can adhere more effectively to different types of surfaces, significantly enhancing its performance and versatility in various applications such as climbing. A material exhibiting adhesion properties dependent on direction is termed anisotropic. Chemically, anisotropic adhesive substances can be made from various materials such as resins, adhesives, rubbers, polymers, or elastomers.

Polyurethane is a substance that is easy to process but has low resistance to mechanical damage. It is used in the production of flexible fibers. In the context of Stickybot's paw, polyurethane is implemented to create flexible elements of the paw, facilitating movement and adhesion to surfaces (Kim, S. et al., 2007).

III. Jumping – Biological inspiration for creating mechanics that enable robots to jump primarily comes from animals such as kangaroos and frogs, which, due to their long legs, utilize leverage during jumping, as well as insects like fleas or grasshoppers, which have shorter legs and use the force of propulsion, relying on energy accumulated in their hind limbs. This mechanism can be based on the principle of constriction, involving the contraction of muscles and increased tension in tendons, which are then released, unleashing the accumulated energy and causing rapid acceleration of the jumping robot.

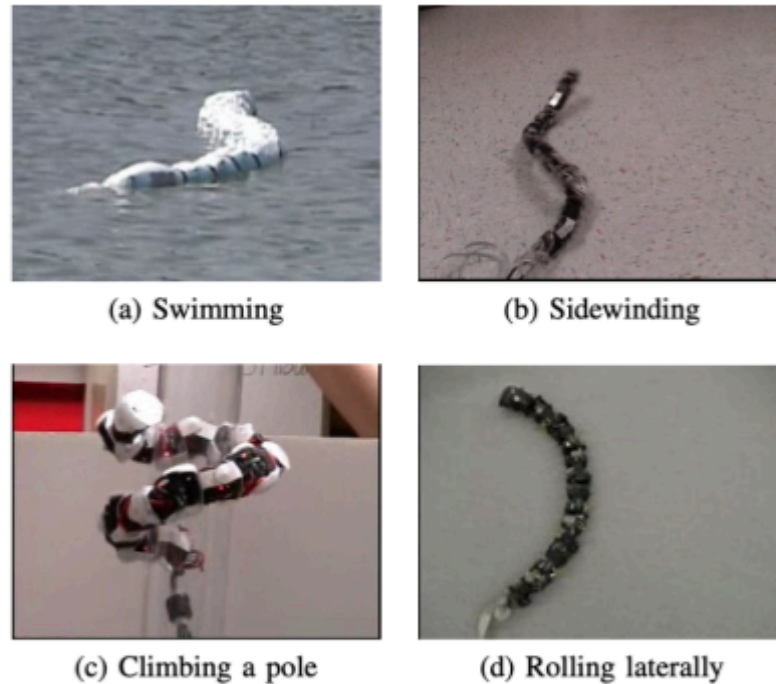
Biomimetic jumping robots perform well in challenging conditions, demonstrating a high ability to navigate obstacles and being well-adapted to move across various surfaces. Due to these capabilities, robots employing this method of locomotion are often utilized in space exploration or military operations. A robotic flea designed in Seoul, for example, was capable of jumping to a height of 71 cm, which is 14 times its own height. The length of the flea's jump reached 100 cm, constituting a 20 times increase over its own length (Nguyen, Q.V., Park, H.C., 2012).

IV. Slithering – The inspiration for designing crawling robots is primarily derived from snakes, whose methods of movement can be categorized into:

- Serpentine Movement – various parts of the snake's body move sideways, which is effective on flat terrain;
- Rectilinear Movement – appropriate for narrow spaces, this movement relies on the cyclical contraction and relaxation of muscles;
- Concertina Movement – similar to serpentine movement, snakes use it for climbing trees;
- Sidewinding Movement – characterized by a spiral pattern, allowing for lateral or inclined positioning of the body.

Scientists drew inspiration from rattlesnakes when developing the level of flexibility that a robotic snake should achieve.

The Unified Snake Robot (USR), inspired by the mechanisms of snake locomotion, excels in tasks requiring movement in narrow spaces and is also capable of obstacle avoidance. It possesses sixteen degrees of freedom, and the connection between adjacent joints is perpendicular. The USR utilizes advanced algorithms and sensory systems that enable it to analyze its environment, navigate around obstacles, and make decisions regarding its movement. Consequently, the robot can autonomously navigate challenging conditions, minimizing the need for human intervention. The movement of the robotic snake may be constrained due to its power supply method, as some models require connection to an external source, such as electricity, to operate. This limits their mobility and operational range, as they must remain close to the power source. However, not all models of robotic snakes necessitate connection to an external source; some can operate on battery power or other forms of energy, enhancing their mobility and versatility of application (Tesch, M., Schneider, J., Choset, H., 2011).



Img. 2 Ways of Locomotion in Robotic Snakes
 Tesch, M., Schneider, J., Choset, H. (2011) *Using Response Surfaces and Expected Improvement to Optimize Snake Robot Gait Parameters*, in: *IEEE International Conference on Intelligent Robots and Systems*, p. 1077.

The method of fish movement in water can also be likened to crawling; therefore, biomimetic robots imitating fish have been developed. These robots utilize movement mechanisms that are technically similar to those used in the production of robotic snakes. Robotic fish serve as an alternative for research systems to analyze underwater spaces because, according to scientists Zihang Gao and Qing Shi, along with their collaborators, they move much more efficiently than most currently used research devices. They are adapted for prolonged use and can swiftly cover long distances.

V. Flying – Birds and bats, owing to their energy efficiency and flight movement styles, serve as excellent subjects for research in the construction of biomimetic flying robots. Researchers pay attention to factors such as the mechanism and structure of flight when designing flying robots. The way wings move, including the frequency and amplitude of the movement, plays a significant role in achieving efficient and stable flight. This mode of locomotion results in high performance, reliability, and flexibility of movement.

At present, one of the most impressive flying robots is the Smartbird, designed by the company Festo, which offers innovative solutions in the fields of automation and technical education. This seagull-inspired robot is made of glass and carbon fiber as well as polyurethane foam to reduce its weight. It measures one meter in length, has a wingspan of about two meters, and weighs less than half a kilogram, which is an impressive achievement. The robotic bird is aerodynamic, and its movements during flight are nearly identical to those of a live seagull (Send, W. et al., 2012).

1.2 Cognitive functions of biomimetic robots

Biomimetic robots can fulfill various cognitive functions. They can be equipped with sensory systems that mimic the senses of living organisms (vision, hearing, touch, taste, and smell). Following the example of biological organisms, they can learn, either evolutionarily, using evolutionary algorithms, or in a controlled manner, including through reinforcement. Biomimetic robots may also possess the ability to plan and make decisions, depending on preferences, goals, and available information. Below, I briefly discuss selected cognitive functions related to sensory exploration.

The reception of visual stimuli in robots typically occurs through the use of bionic eyes, which mimic biological mechanisms observed in animals and strive to replicate these mechanisms. The navigation method and position of the robot are also crucial for the visual stimuli it perceives. For instance, a group of American scientists, including Young Min Song, Yizhu Xie, Viktor Malyarchuk, and others, developed a sophisticated project involving bionic eyes. They combined advanced optical devices with flexible matrices of silicone photodetectors, allowing the eye to have a hemispherical shape and capture a wide field of view. In the design of robot vision, it is essential to consider positioning algorithms for the robot and its sensors, as well as to create a map of the space accessible to the robot (Song, Y., Xie, Y., Malyarchuk, V. et al., 2013).

The sense of hearing in robots is typically employed for the recognition and localization of sound sources. Peter Bobbins, drawing inspiration from echolocation used by dolphins, designed a biomimetic robot that effectively captured sounds and, using an echo-sounder, determined the location of objects in shallow water tanks (Dobbins, P., 2007).

Sensory receptors in robots can be located in artificial skin or mechanical sensory hairs inspired by animal vibrissae. Synthetic skin in biomimetic robots can be made of

polyvinylidene fluoride, a highly durable material characterized by thermoplasticity and resistance to chemical factors. Sensors made from this material are capable of mimicking tactile sensing, as well as proprioceptive sensing, enabling the robot to determine its position in space. Sensory technologies respond to changes in temperature, physical contact with the environment, with the ability to determine the force of applied stimuli (Gao, Z. et al., 2019).

Chapter 2

Characteristics of the WR-5 Robot

The increasing number of patients suffering from mental illnesses has led to the development of animal research aimed at improving patient treatment. Rats and mice, due to their genetic similarity (their genome is close to the human genome) and their good response to pharmacological treatment, are often used to create models of mental illnesses. They are highly useful for research aimed at improving psychological and psychiatric treatment methods because they are socially highly functioning animals. Laboratory animals undergo genetic manipulation, neurological operations, are subjected to psychotropic drugs, or exposed to stressful environmental factors. Animal models of mental illnesses represent phenotypes such as plastic changes in the brain or behavioral problems in patients with psychiatric disorders. These models are most commonly evaluated through the study of social interactions and animal behavior.

The robotic rat WR-5 has been utilized for research on animal models of psychiatric disorders. Manipulating a group of live rats is complex and may not yield the intended effects, as humans cannot influence a rat in the same way as another member of its species could. Therefore, incorporating a robotic rat into research allows for relatively easy manipulation of animal behavior, leading to a more precise verification of research hypotheses. From a scientific perspective, biomimetic robots significantly facilitate studies on animals conducted in the context of social interaction (Shi, Q. et al., 2012b). The WR-5 robotic rat was designed by nine scientists from Waseda University in Tokyo, hence its name, Waseda Rat fifth generation⁶.

Scientists argue that the design and technologies employed in the WR-5 robot project are sufficient to achieve satisfactory results in the field of interaction with a group of live specimens. Previous versions of the robot provided research results that were insufficient to formulate a clear hypothesis regarding the social functioning of the robotic rat.

2.1 The successive development in the generations of Waseda Rat

The first article on the WR-1 robot was published in 2009. During the design of the first-generation robotic rat, scientists utilized X-ray scans of an adult rat's skeleton.

⁶ At the time of writing this work, the WR-5 robotic rat represents the latest model documented in scientific publications. The selection of this robot version is justified by its presence in research relevant to my work, and its advanced capabilities enable it to influence rodents (author's note, May 2023).

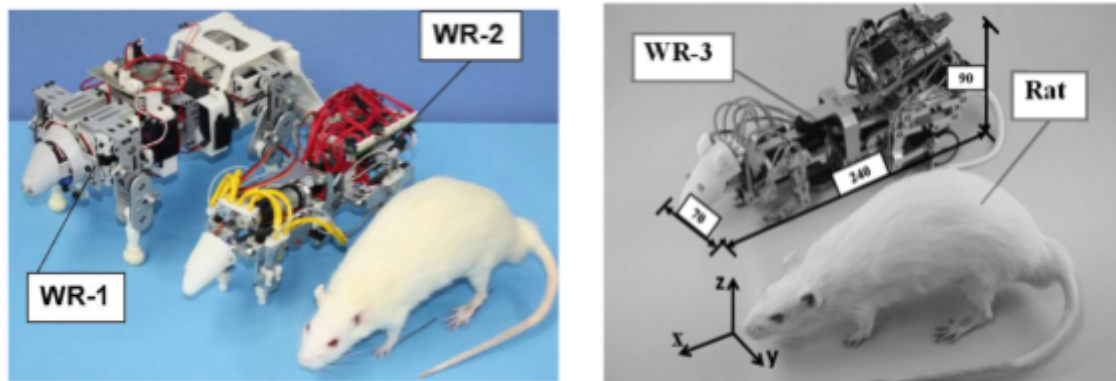
They created a robot schema considering degrees of freedom, indicating where the mechanical model should have movable parts. Through motion analysis of the rat using a transparent floor, scientists observed that the rat moved in two ways. Its gait resembled crawling, while during running, it lifted the right front and left hind legs in the first phase and the left front and right hind legs in the second phase. The WR-1 was remotely controlled and battery-powered, located at the rear of its body to maintain the center of gravity. The robotic rat could imitate the walking and running of a rat in different directions, but it did much slower than a living animal. It could also move its head and stand on its hind legs, which was supposed to help in social interaction. Due to distinct differences between live rats and the WR-1 robotic rat, scientists could only observe basic elements of social interaction in rats, such as sniffing and standing on hind legs. Such behaviors were insufficient to confirm the hypothesis that the robotic rat could establish a relationship or influence a live member of the species (Ishii, H. et al., 2009).

The biomimetic robot should be of similar size and possess motor capabilities closely resembling those of the species it draws inspiration from in its construction. Based on previous research, scientists have observed that freedom of movement and enhanced capabilities in social interaction are essential to achieving intended research outcomes. Therefore, the subsequent version of the robotic rat, WR-2, was designed to mimic the movements of a live rat, and its size did not exceed that of an adult male. A meticulous analysis of the rat's movement allowed determining the mobility scheme of the mechanism and creating a model with fifteen degrees of freedom, a flexible spine, and one movable joint in each limb. The robot's limbs were also equipped with motors converting electrical energy from direct current into mechanical energy – DC motors. The robot's parameters are presented in the table below, providing a comparison with the previous version of the robotic rat and a live representative of the species.

Robot or Rat	WR-2	Rat[19]	WR-1
Dimension	240 × 70 × 90 mm	240×70×80mm	270×130 ×110 mm
Weight	850 g	400g	1150 g
DOF	15	—	15
Elbow • Knee (Movable range)	135°	135°	135°
Shoulder • Hip Pitch (Movable range)	90°	90°	120°
Shoulder • Hip Roll (Movable range)	50°	50°	50°
Neck (Movable range)	60°	60°	45°
Waist Pitch(Movable range)	90°	90°	120°
Waist Yaw(Movable range)	180°	180°	60°

Img. 3 Comparison of Parameters between Robots WR-1 and WR-2 with a Living Rat
Qing Shi et al. (2010) *Development of a novel quadruped mobile robot for behavior analysis of rats*, in: *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2010)*, p. 3075.

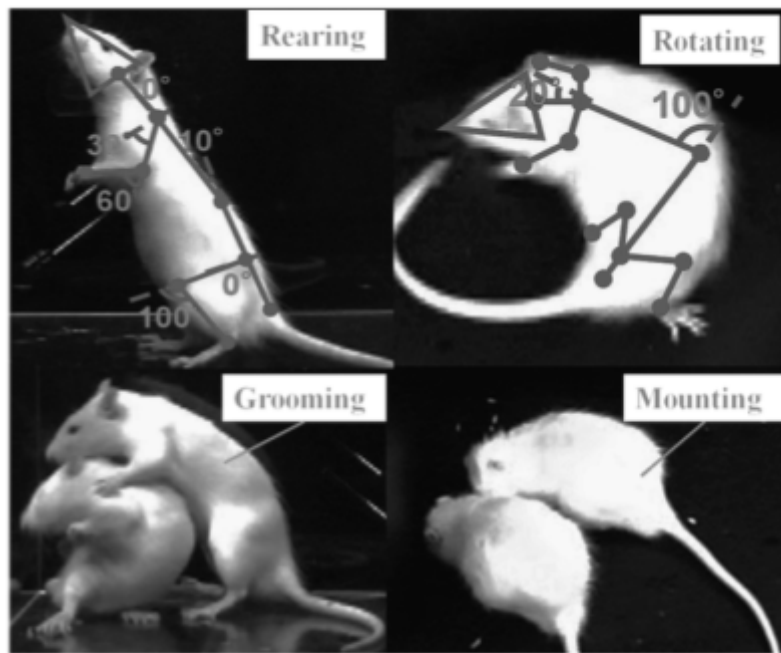
The robot's controller was programmed to control twelve DC motors and three servo motors⁷, resulting in a more natural way of movement and increased social interaction capabilities of the robotic rat. However, studies revealed that the robot's gait was occasionally unstable and inconsistent, which ultimately hindered its interaction with live rats (Shi, Q. et al., 2010).



Img. 4 Visual Comparison of the First Three Generations of Waseda Rat with an Adult Specimen
Po prawej: Shi, Q. et al. (2010) *Development of a novel quadruped mobile robot for behavior analysis of rats*, in: *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2010)*, p. 3073.
Po lewej: Shi, Q. et al. (2011) *Development of a Hybrid Wheel-Legged Mobile Robot WR-3 Designed for the Behavior Analysis of Rats*, "Advanced Robotics", 25, p. 2257.

⁷ A servo motor is a direct current motor characterized by high precision and speed of operation. It enables control over angular or linear position, as well as speed and acceleration (Haider et al., 2018).

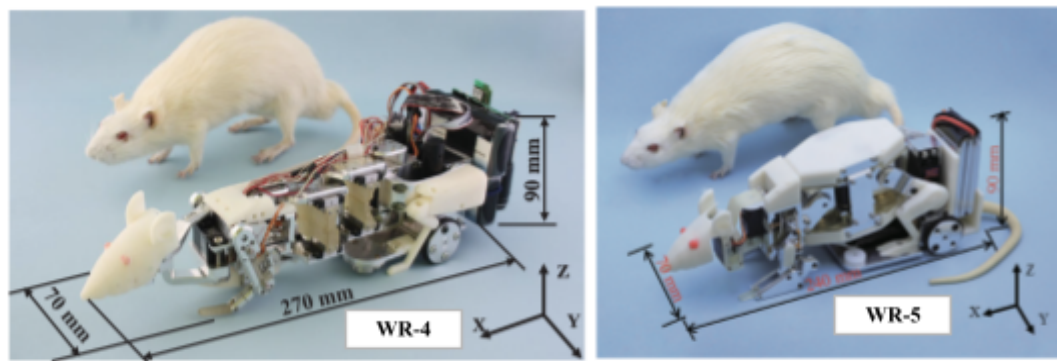
The third-generation Waseda Rat robotic model was the first to be equipped with wheels for fast movement, as well as limbs designed to mimic the social behaviors of rats. Scientists improved upon their previous designs by creating a robot whose body shape and dimensions closely resembled a live animal. WR-3 could perform all observed social interaction-related activities seen in live rats, such as rearing, rotating, grooming, and mounting. The time it took for the robot to perform these activities was very close to the time taken by the rodent, with the greatest time difference being 20 milliseconds.



Img. 5 Activities Related to Social Interaction
 Shi, Q. et al. (2011) *Development of a Hybrid Wheel-Legged Mobile Robot WR-3 Designed for the Behavior Analysis of Rats*, "Advanced Robotics", 25, p. 2259.

Researchers conducted preliminary studies on three groups of rats to investigate the influence of body shape on the outcomes of social interactions. Each rat was sequentially subjected to interaction with WR-3 in the first group, WM-8 (Waseda Mouse) in the second, and a toy rat in the third. Initially, the robotic mouse or rat/toy chased the live rat and then remained motionless. The studies revealed that rats were more inclined to approach and attempt to interact with an object that resembled them in shape. As a result, the fewest rats approached the motionless WM-8, and the most approached WR-3, which had the most similar shape. Final social interaction studies were conducted on two groups of eight-month-old rats, continuously lasting for 6 days. Each day, each rat underwent a ten-minute interaction with the WR-3 robot. In the first

group, the interaction with the robot consisted of the robotic rat chasing the live rat and occasionally rearing on its hind legs. Meanwhile, in the second group, the robotic rat did not move its limbs or engage in social interaction with the live rat but only chased it. Over time, the rats became accustomed to the presence of the WR-3 robot, but in the first group, where the robot exhibited social behaviors similar to those of live rats, this adaptation process occurred more quickly (Shi, Q. et al., 2011).

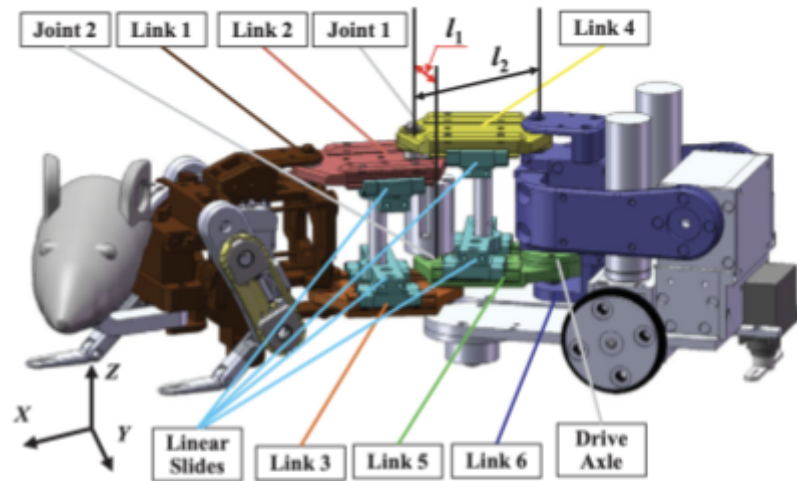


Img. 6 Visual Comparison of Robots WR-4 and WR-5 with an Adult Specimen

Po prawej: Shi, Q. et al. (2012) *A rat-like robot WR-5 for animal behavior research*. in: *2012 IEEE International Conference on Robotics and Biomimetics (ROBIO)*, p. 785.

Po lewej: Shi, Q. et al. (2013) *A rat-like robot for interacting with real rats*. "Robotica", 31:8, p.1338.

Previous studies allowed researchers to improve the design and create another model of the robotic rat – WR-4. The electrical connections and robot's power supply remained the same as in its previous version, but from a mechanical point of view, the new model was significantly enhanced. The degrees of freedom of the robot were distributed as follows: the front limbs, with two active degrees of freedom, ended with paws with two passive degrees of freedom. Additionally, one degree of freedom was installed in the tail, one in the neck, and two more in the torso. Underdeveloped motion mechanisms in the front limbs, neck, and waist of WR-3 impeded the robot's interaction with rats. Therefore, scientists focused on these three aspects in the design of the fourth version of Waseda Rat. In the construction of the waist, a six-bar linkage mechanism was used – a connection of six bars with six joints allowing the movement of one bar relative to another. This mechanism enabled the bending of the robotic rat's body at various angles.



Img. 7 Mechanism of WR-4 Robot
 Shi, Q. et al. (2013) *A rat-like robot for interacting with real rats*. "Robotica", 31:8, p.1343.

Increased mobility in the neck allowed for a better imitation of the movement of a live rat when making the torso turn. Additionally, the symmetrical use of lightweight sonic motors⁸ in the front limbs enabled the robot to move smoothly and naturally during social activities, such as grooming. It is worth noting that grooming and climbing were not activities naturally performed by the robot and ultimately did not achieve the intended effects in initiating interaction. Before conducting the actual research, the WR-4 robot underwent an assessment of motion functionality, which demonstrated that the robot was able to match the running speed of a live rat. The elements of standing on hind legs and rotating had to be modified, but the remaining mechanisms met the researchers' requirements.

In interaction with rodents, the robot learned the behavioral patterns of rats, allowing the final studies on social interaction to be conducted without human intervention. The robot exhibited friendly behavior in the experimental group and neutral behavior in the control group. In the experimental group, the robot performed actions indicating excitement and a willingness to establish a relationship. Initially, it tracked the observed object and then mimicked its actions. In the control group, however, WR-4's only programmed activity was tracking the experiment participant. The studies showed that rats in the experimental group were willing to engage in interaction and were more active. Observations of the interaction between live rats

⁸ Sonic motors (also known as piezoelectric motors) are electric motors that generate energy by converting acoustic vibrations into microscopic mechanical work. Their construction involves utilizing the vibrations of piezoelectric elements and surface waves (Koc, B., Spanner, K., 2016, p. 1).

revealed that the locomotive abilities of the robotic rat are not yet developed enough to match the interaction between two live rats with an active disposition. However, the results of the interaction between the rat and the robot were close to the results of the interaction between two live rats with a calm demeanor, indicating the success of the study. Due to the body structure, WR-4 posed difficulties in control, and its mechanism for avoiding moving obstacles, i.e., other live rats. It was too primitive to enable the study of group interactions between rats and the robot. Considering the insufficient naturalness of the performed activities and the inability to imitate grooming or climbing, researchers began working on the next model (Shi, Q. et al., 2013).

2.2 The technical parameters and operational mechanisms of WR-5

The robotic rat WR-5 is the ultimate result of long-term work, and for the first time, it met the criteria required in studies on animal models of psychiatric disorders. None of its previous versions were able to perform all four types of activities classified as social behaviors of rats, namely rearing, grooming, rotating, and climbing. Studies have shown that the situation in which a rat periodically rears on its hind legs and climbs on another rat is perceived as aggressive and dominant behavior. Consequently, it reduces the willingness to show friendship in acts such as grooming and, over time, may even lead to apathy in rats.

In order to create an accurate model of the robot's structure, scientists used X-ray scans of a rat's body performing various activities. Examining the rat's skeletal architecture enabled a precise analysis of the mechanism's construction and optimal distribution of degrees of freedom in the robotic rat. X-ray scans revealed that standing on hind legs involves lifting the hips and straightening the spine. When climbing on another rat, the hind legs are bent, and the spine forms a gentle arch. Grooming, on the other hand, requires a complete bend of the spine and neck to allow the rat to easily reach the base of the tail. Previous studies indicated that a four-legged robot could not move fast enough to catch a running rat, and interaction with live rats required four limbs. Therefore, the robot's activities were divided into two categories: movement and interaction. Based on observations in the WR-5 project, three movable parts of the spine were considered, wheels placed at the back of the mechanism to achieve a speed comparable to a live rat, and four legs for better mimicking social behaviors. The wheels aim to improve the robot's locomotion, while movable limbs, torso, and neck allow for building relationships. To achieve natural movement, the robot was designed

orientation in the vertical plane, and the robot raises or lowers part of its body, such as when standing on its hind legs. The movement of the robot's neck was programmed to allow the head to rotate right or left, depending on the activity being performed. Therefore, the mechanism required no more than two degrees of freedom and is powered by two easily controllable servo motors. The movement of the front limbs was achieved using a slider-crank mechanism¹⁰ powered by ultrasonic motors, two of which were symmetrically placed in the robot's body, enabling rotation around the lateral axis and simultaneous movement of the arms. The third motor drove the movement of the robot's elbow joints (Shinder, M.E., Taube, J.S., 2019, Shi, Q. et al., 2015b).

To control the robot's motors (a total of four DC motors, two servo motors, and six ultrasonic motors), a compact controller using PWM¹¹ technique was designed. The main control center for the robot was a desktop computer, where researchers could oversee the progress of the experiments. The activities of the robotic rat were programmed according to the research needs and did not require changes during the experiment. If necessary, behavioral modifications could be introduced in real-time using microcontrollers employing Bluetooth technology. The signal from the controller was immediately received and processed by the microcontrollers, which implemented changes in motion. The robot also featured 3.7-volt Li-polymer batteries with a capacity of 1350 milliampere-hours, providing approximately an hour of continuous operation. To construct WR-5, materials were chosen to minimize its weight and allow it to match the weight of a live rat. Consequently, the robot was primarily made from an aluminum alloy, while the head was crafted from plastic.

The programming of the posture and trajectory of the robot was carried out using VIM software¹². The model outlined by the scientists using this software determined the robot's movement, influencing the connections of various parts of

¹⁰ The slider-crank mechanism is a mechanism that converts the rotary motion of one element into linear motion or vice versa. It consists of two main parts: the crank and the slider. The crank is a bar that rotates around a central pivot point. One end of the crank is connected to another element, such as a piston, rod, or rotor, which performs rotary motion. The other end of the crank is connected to the slider. The slider is a short element that moves along a straight line in response to the crank's motion. The slider can be connected to another element that utilizes linear motion to perform a specific action, such as driving a machine or moving an object (Miller, S., 1996, s. 81-83).

¹¹ Pulse Width Modulation (PWM) is a technique for controlling analog circuits using digital signals. It has various applications, including adjusting the brightness of LED lights or the volume of sound. PWM operates by manipulating the width of the current pulse, affecting the amount of power (Iswardani, K., Rusdiansyah, A., 2018).

¹² I believe that the VIM text editor used by the scientists was not the optimal tool, as it is slow, and more complex code often leads to program crashes. In 2015, there were already many competitive programs, such as Visual Studio Code or Neovim, which I personally consider better programming tools (author's note).

WR-5: head, neck, torso, and hips. Therefore, the mechanism included four connections that could be influenced by three different forces: the force generated during the interaction with a live rat, the force of external factors, or the force exerted by one connection on another. In the interaction process, the side observer or obstacle will be ignored by the robot during the study. Thus, the robot will try to avoid other rats in the group and follow its target, generating an attractive force towards the head of WR-5, meaning the robotic rat chases its target by moving its head forward (Shi, Q. et al., 2015b).

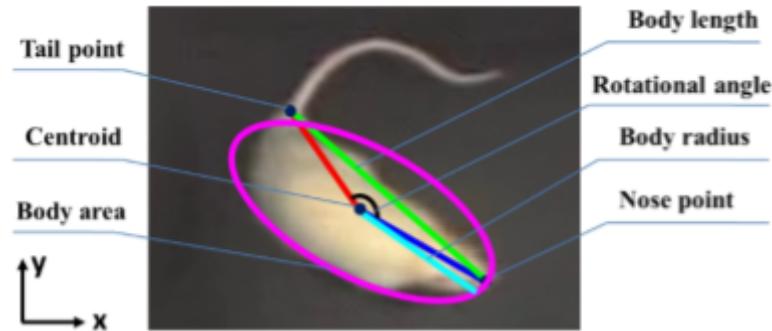
Sensory mechanisms used in the WR-5 robot were designed during work on its predecessor, the WR-4. The recognition system of the robot aimed to enable real-time identification of living rat activities to ensure natural interaction between the rat and the robot. This system was based on methods of direct analysis and classification of recorded images. The ability to distinguish the following activities proved particularly important: movement, grooming, standing on hind legs, and turning. Movement can be easily recognized as it involves spatial relocation, which is straightforward to record. The other activities were meticulously analyzed to create a functional sensory plan for the robot.

Researchers used images from social interaction studies with the robotic rat WR-3 to create a geometric model of a live rat, a foundational step in the design of the robot's sensory system. WR-5 needed to distinguish the rat from the environment, which couldn't rely solely on observing the brighter elements in the recorded image. Typically, a black background was used in studies, necessitating an assumption that light reflections would also create white spots on the image, potentially causing WR-5 to misunderstand reality. Thus, a contour-finding method from the OpenCV¹³ library, a tool utilized by researchers in designing sensory mechanisms, was applied. For correctly positioning the live rat, it was essential for the robot to identify the centroid, the nose point, and the tail base.

The mentioned three points were extracted using an image processing algorithm. Thus, once WR-5 located the rat, it had to analyze the pixels and their coordinates, enabling it to determine the centroid of the rat's body. Establishing the centroid allows the robot to accurately position the live rat within space and track it, which is a significant behavior in studies of social interaction. The tail base can be identified as the

¹³ OpenCV is a free software library used for developing computer vision and machine learning applications (<https://opencv.org>).

point closest to the centroid, while the nose tip serves as the point farthest from the centroid within the geometric model. The rat's body is long and narrow, allowing its area to be outlined with an ellipse. The body length is calculated as the distance between the tail base and the nose tip, while the body radius is defined as the maximum possible distance between the body contour and the centroid (Shi, Q. et al., 2012a).



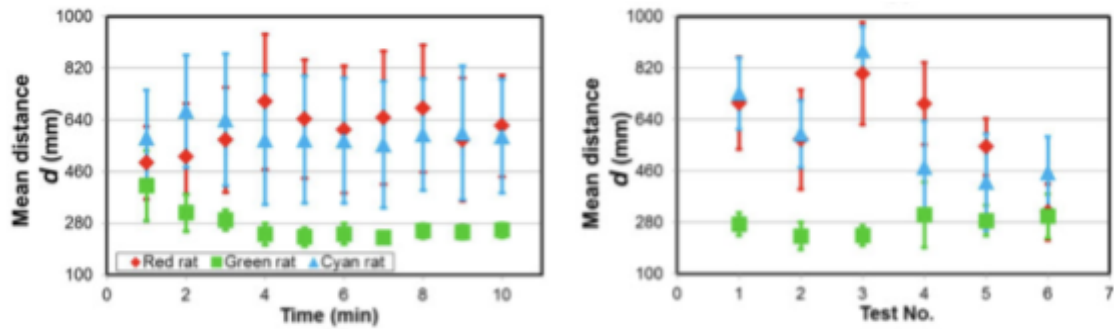
Img. 9 Geometric Model of a Real-Life Rat
 Shi, Q. et al. (2012a) *Image processing and behavior planning for robot-rat interaction*, w: *International Conference on Biomedical Robotics and Biomechatronics*, pp. 968.

The next step in the design of the WR-5 sensory mechanism was to implement classification methods for rat behavior, one of the most crucial elements ensuring successful social interaction. The creation of an N-dimensional point set allows for the division of received images into two categories using a kernel function, which is employed in data analysis derived from the real world. The kernel function enables the transformation of input data into a higher dimension, facilitating separation along hyperplane lines, thereby enhancing the differentiation of the two image categories. In short, the kernel function transforms data from one space to another where they are more separable (Shi, Q. et al., 2012a). Typically, in machine learning, a linear model suffices; however, for correctly analyzing visual stimuli, data should also be presented with greater consideration of additional variables, thereby adopting a nonlinear model. Linear models assume that the target variable can be expressed as a linear combination of input features. These models seek dependencies between input features and the output value, which can be articulated through a simple formula. This formula includes parameters assigned to each input feature and multiplied by the value of that feature. Each feature is multiplied by its corresponding weight or coefficient, which are then summed.

A nonlinear model, in contrast to a linear model, posits that the relationships between input features and the output value (target variable) cannot be expressed through a simple linear formula. In nonlinear models, the relationship between input features and the output value may take on a more complex form, encompassing other intricate relationships, such as interactions between features. Nonlinear models can be employed in the creation of artificial neural networks, where each neuron applies an activation function to the weighted sum of its inputs. Neural networks may have multiple hidden layers, allowing them to learn complex, nonlinear dependencies between input features and the target variable (Hofmann T., Schölkopf B., Smola A.J., 2008).

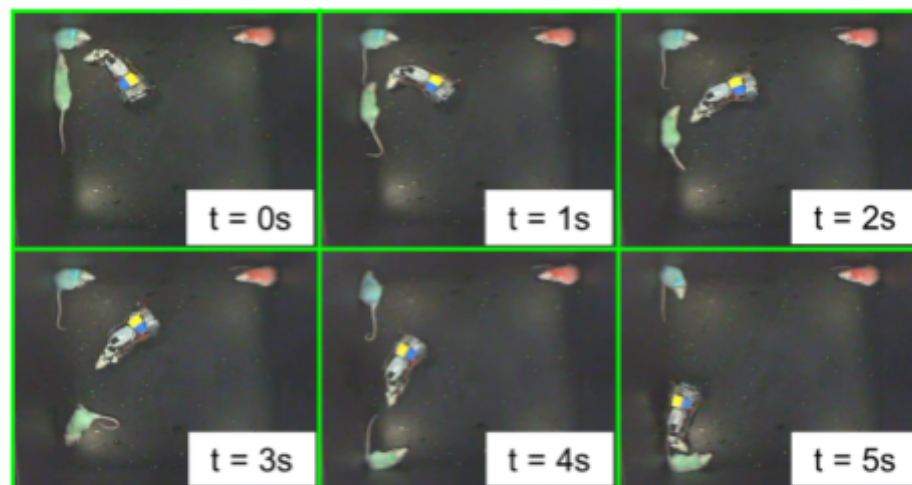
The functionality of the sensory system was tested on the WR-4 robot. The experiment was conducted without human intervention. The stimuli recorded by the robotic rat were processed in real-time, enabling the robot to respond with pre-programmed behaviors. During the studies involving three eight-month-old rats, each subjected to a ten-minute interaction with WR-4, errors in the robot's recognition of social activities were examined. The results indicated that WR-4 relatively frequently misclassified the behavior of standing on hind legs as turning, and sometimes as grooming; however, the accuracy of categorization was determined to be around 90%. Despite the defects in the robot's sensory system, the mechanism met the researchers' requirements. The recognition, categorization, and imitation of a live rat's activities could take place in real-time without the researchers' intervention, which not only ensured a better quality of interaction between the robot and the animal but also streamlined the research process (Shi, Q. et al., 2012a).

To verify the correctness of the program written for the robot, experiments were conducted using three nine-month-old male rats. To distinguish among them, one was marked with blue, another with red, and the third with green. The task for WR-5 was to follow the green rat while simultaneously avoiding the others. The experiment was conducted six times. Every minute, the distance between the rats was measured, and the analysis of the results showed that the distance between the robot and the green rat ranged from 25.5 to 40.9 cm, while the distance between the other rats varied from 49.1 to 70.3 cm.



Img. 10 The recorded distances of the WR-5 robot from the other participants in the study Shi, Q. et al. (2015b) *Design and Control of a Biomimetic Robotic Rat for Interaction With Laboratory Rats*. “IEEE/ASME Transactions on Mechatronics”, 20:4, pp. 1838.

The above illustration depicts the changing distances between the rats over the course of a single experiment and across subsequent trials of the interaction. They indicate that the rats gradually became accustomed to the robot's presence; however, in most cases, they exhibited fear towards it. The pursued rat appeared to be defenseless in its interaction with the robot. During the experiments, the posture of WR-5 was continuously adjusted based on the body positioning of the live rats, suggesting the potential to create a high degree of similarity between the robot and the biological inspiration for the mechanism (Img. 11). The experiment demonstrated that the robot's software functions correctly. The trajectory and movement patterns can be adapted to the situation, even if it involves more than one participant in the study. Therefore, WR-5 can be utilized in research on animal models of mental illnesses (Shi, Q. et al., 2015b).



Img. 11 Tracking of the green rat by the robot Shi, Q. et al. (2014) *Control of posture and trajectory for a rat-like robot interacting with multiple real rats*. w: *IEEE International Conference on Robotics and Automation (ICRA)*, pp. 979.

Chapter 3

Research and Evaluation of the WR-5 Robot Interaction with Rats

Rats are known as social animals and benefit from being in groups. They have a natural tendency to form communities and establish bonds with other rats. Group interactions provide them with a sense of security, opportunities for cooperative food gathering, and access to shelter. In natural conditions, they live in rapidly growing colonies, with their most common habitat being urban areas (Schweinfurth, M.K., 2020). The behavior of a rat is highly influenced by the presence of other members of its group. Therefore, inducing interactions between a laboratory rat and a robotic rat, which resembles a live rat in size and movement characteristics, is relatively straightforward. For instance, conducting a similar experiment with cats would be significantly more challenging, as cats are solitary creatures and their social interaction markedly differs from human social interaction models. Consequently, the experiment with WR-5 used in research on animal models of mental illnesses yielded the desired results. The studies presented below on social interactions between live rats and WR-5 demonstrate that the robot can modulate rodent behavior (Shi, Q. et al., 2015a).

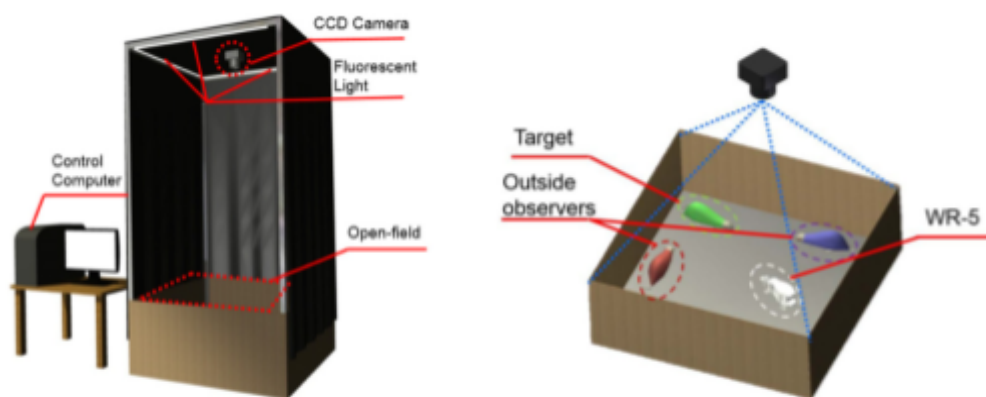
3.1 The impact of WR-5 on rat's behavior

Upon completing the design work on the WR-5 robot, it underwent a functionality assessment aimed at examining the reactions of live rats to climbing behaviors. Previous versions of the robot were unable to perform this activity in a way that impacted the behavior of the test animals. Climbing onto another individual is considered one of the most fundamental social activities among rats. It serves as an expression of dominance and aggression, but it is also noticeable during play or sexual interactions. Additionally, it is the only activity of the robotic rat that requires direct contact with the animal.

For the study, the participating rodents were divided into two groups: A and B. The experiments lasted a week, with each rat undergoing one research session daily, during which a seven-minute interaction with the WR-5 robot occurred. In Group A, WR-5 chased the rat, while in Group B, the robot followed the rat, climbing every minute. The researchers measured the amount of movement performed by the animals and the frequency of behaviors such as grooming and standing on hind legs. Rats in Group B exhibited more movement; however, the frequency of standing on hind legs was lower

than in Group A, and grooming occurred almost not at all. The increased mobility in Group B rats suggests they were attempting to avoid the robot, while the gradually decreasing frequency of standing on hind legs and exploration of their surroundings indicates that the Group B rats may have experienced stress and fear in response to the robot. The study demonstrated that the robotic rat WR-5 is capable of inducing negative effects on the well-being of the test rats and, consequently, could be utilized in research involving animal models of mental illnesses (Shi, Q. et al., 2012b).

For the study of interactions between WR-5 and a group of rats, thirty-six adult males weighing approximately 5.3 grams each were utilized. The rats were divided into two groups, A and B, each consisting of eighteen individuals. Group A included F-344/Jcl rats, while Group B contained Long-Evans rats. Both groups were further divided into subgroups of three rats each. One rat from each subgroup was selected to serve as the target for WR-5. The remaining two rats in the subgroup acted as peripheral observers. To distinguish between the rats, they were color-coded; similar to the experiment presented on page 21, the target rat was marked in green, while one observer was colored red and the other blue.



Img. 12 Schematic diagram of the experimental space

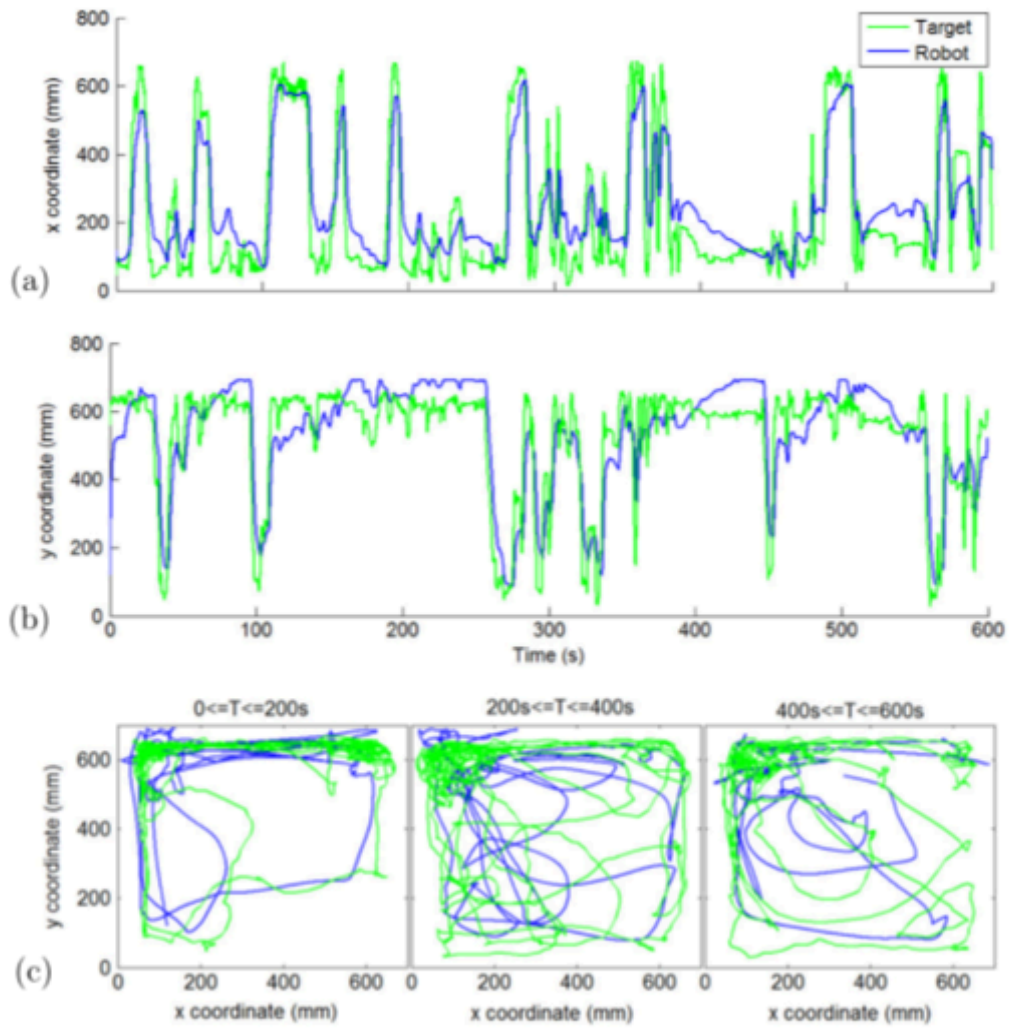
Shi, Q. et al. (2015a) *Behavior modulation of rats to a robotic rat in multi-rat interaction*. "Bioinspiration & Biomimetics", pp. 3.

The illustration above shows the experimental space designated for conducting the experiments. It consists of a research area measuring 700 mm by 700 mm, surrounded by wooden walls that are 600 mm high. Black curtains were hung around the area to separate the research space from external distracting factors. A CCD¹⁴ camera was

¹⁴ The CCD camera contains a charged-coupled device (CCD) on its integrated circuit, which is a type of transistor light sensor. CCD devices convert or manipulate electrical signals, generating some form of output, including digital values. In photographic cameras, the CCD facilitates the capture of visual information and its transformation into an image or video. In short, CCDs are essentially digital cameras (Mullikin, J. C. et al., 1994).

mounted above the container where the study took place, connected to a control computer via Bluetooth technology. The research area was illuminated by four 20-watt fluorescent lamps designed to simulate natural lighting.

Each subgroup underwent seven ten-minute sessions. The first session, referred to as the pre-interaction phase, was conducted without the robotic rat, allowing the three test rats to move freely within the research space. The subsequent five sessions focused on studying the interactions between the rats and the robot, while the last phase, the post-interaction phase, again involved the three live rats being confined within the research space without exposure to the WR-5 robot. During the interaction phase, WR-5 continuously pursued the green rat while simultaneously avoiding the red and blue rats. To prevent direct contact between WR-5 and its target, a maximum proximity distance of 100 mm was established. The distances between the green rat and WR-5 were assessed using footage from the cameras, determining their positions using x and y function plots. Below is an illustration depicting the distances between the robot and the rat being chased, measured during one session, with time indicated in seconds. The analysis of the graphs presented in the illustration indicates accurate tracking of the green rat by WR-5 in real-time. For most of the duration, the distance between the head of the robotic rat and its target ranged from 10 to 20 cm, which clearly illustrates the success of the interaction conducted.



Img. 13 The distance of WR-5 from the tracked rat
 Shi, Q. et al. (2015a) *Behavior modulation of rats to a robotic rat in multi-rat interaction*.
 "Bioinspiration & Biomimetics", pp. 4.

The researchers utilized monitoring software to extract the contours of the bodies of the rats and the robot from the CCD camera recordings. The blue and yellow tape placed on the back of the WR-5 mechanism made it easy to distinguish from other participants in the study. With the drawn contours, even the coordinates of the rats' noses and tail tips could be accurately measured. During the examination, the movement activity of the rats within the research space was monitored, along with the frequency of behaviors such as grooming, standing on hind legs, and engaging in direct contact through climbing. The aim was to determine the relationships among the rats and their willingness to establish connections with one another. Movement, standing on hind legs, and grooming were characterized as behavioral activities, while climbing was regarded as a social activity. The collected data proved to be evenly distributed, as

determined by the Shapiro-Wilk test (Shapiro S.S., Wilk M.B., 1965)¹⁵. This test assesses the normality of data distribution within a sample. In the population of rats, it can be used to check whether the distribution of certain traits or variables (such as weight and body length, hormone levels, and behavior) observed in the studied rat population resembles the normal distribution seen in a control group. To evaluate the relationship of the peripheral observers with the robot, the time spent by each rat within a distance of no more than 10 cm from the robot was measured. To assess changes in the attitudes of the peripheral observers, the measured distances from the first, second, and fifth days of the study were compared. The pre-interaction and post-interaction phases of the test were compared to investigate the impact of WR-5 on the behavior of the rats.

The results of the study indicate that the green rat, which served as the target for the robot, displayed significantly greater activity following the interaction with WR-5. The movement activity of the blue and red rats did not increase to a statistically significant degree. The frequency of standing on hind legs among Long-Evans rats showed a slight increase during the tests, while for F-344/Jcl rats, this frequency decreased slightly. On the other hand, the frequency of grooming increased over time, suggesting that the rats gradually became accustomed to the robot. In the case of Long-Evans rats, social climbing activity was observed more frequently in the post-interaction phase than in the initial phase, prior to the introduction of the robot into the research space. No statistically significant changes were observed in F-344/Jcl rats. The peripheral observers in the study, namely the red and blue rats, spent more time in closer proximity to WR-5 on the fifth day compared to the first day; however, the comparison of data from the first and second days did not show significant differences. Upon analyzing the results, it is evident that the behavior of the rats may be influenced by the robotic rat WR-5, and that Long-Evans rats appear to be more susceptible to the robot's influence. This strain was more active during interactions with the robot, resulting in a higher stress coefficient. The peripheral observers seemed to gradually acclimate to the presence of the robotic rat, as indicated by the trend toward reduced distance over the course of the study. The red and blue rats also appeared to be

¹⁵ The Shapiro-Wilk test is a commonly used statistical test that compares the distribution of data to a theoretical normal distribution. It is based on the calculation of a test statistic that measures the degree of deviation of the data from the accepted normal distribution, represented by the Gaussian curve (commonly known as the bell curve or normal distribution curve). This allows for the determination of probabilistic values of the random variable in the collected data. The data distribution will be considered close to normal if its linear plot resembles a Gaussian curve, indicating that regardless of the distribution of factors, the probability of their occurrence is high, and the collected data are statistically significant.

relatively more interested in their surroundings than the green rat. Agonistic behaviors, such as defense or attack, showed an upward trend among the rats targeted by WR-5. Peripheral observers exhibited dominant behaviors (climbing) toward the green rat, suggesting its submissiveness and apathy. Thus, the robotic rat may also indirectly influence relationships within the group of rats. By inducing stress in the chased rat, it alters its behavior and social standing.

In summary, the studies demonstrated that the biomimetic robotic rat can influence a group of rats not only through direct interaction but also by existing within the vicinity of other group members. The research conducted with WR-5 indicates the potential for using the robot in experiments involving animal models of mental illnesses due to its negative impact on the animals (Shi, Q. et al., 2015a).

3.2 Future research opportunities

Since the publication of materials on the WR-5 robot, Qing Shi and his team of collaborating scientists have made significant progress in the construction of biomimetic robots inspired by rats. New models of robotic rats, including the WR-5M, have been developed, potentially offering even greater interactive capabilities.

The design process of the latest model, the Waseda Rat WR-5M¹⁶, was described in the article "A Modified Robotic Rat to Study Rat-like Pitch and Yaw Movements," published in 2018. The researchers aimed to achieve greater mobility for the robot so that its movements would more closely resemble the biological capabilities of a rat. Enhancing the robot's range of motion would facilitate more natural interactions between laboratory animals and the robot. Compared to the WR-5, the improved version, due to its lighter weight and upgraded electronic system, moved faster. The hind limbs were redesigned to maintain three degrees of freedom, while more efficient motors allowed for smoother and longer operation of the entire mechanism. Stepper motors were utilized, requiring significantly less power to achieve the same effect as the sonic motors found in the WR-5's construction. An additional degree of freedom was implemented to connect the head to the torso, enabling more natural head movements during actions such as climbing or standing on hind legs. The robot's capabilities for vertical movement were also optimized, resulting in a more natural form of activities

¹⁶ At the time of writing this work, I did not have access to sufficient studies on the social interactions of the robot, which are currently ongoing, and the results have yet to be published; therefore, this topic does not constitute the main focus of this text (author's note, May 2023).

such as grooming or turning. In summary, the main advantage of the WR-5M is its greater range of motion, allowing for a more accurate imitation of rat behaviors. The researchers hope to conduct social experiments in the future involving this robot, which could yield better results in terms of interaction with live animals compared to previous versions of the Waseda Rat. Below is a table comparing the parameters of WR-5 and WR-5M (Shi, Q. et al., 2018).

	WR-5	WR-5M
Dimensions ($L \times W \times H$)	$\sim 240 \times 70 \times 90$ mm	$\sim 210 \times 70 \times 80$ mm
Weight	~ 800 g	~ 600 g
Maximum speed	~ 1.0 m/s	~ 1.5 m/s
Actuators	DC motor, servo motor, USM	DC motor, servo motor, stepper motor
Power supply	11.1 V rechargeable Li-polymer batteries	12 V rechargeable Li-polymer batteries
Operation time	~ 1 h	~ 1.5 h

Img. 14 Comparison of the parameters of the WR-5 and WR-5M robots
Shi, Q. et al. (2018) *A Modified Robotic Rat to Study Rat-Like Pitch and Yaw Movements*,
“IEEE/ASME Transactions on Mechatronics”, 23(5), pp. 2451.

The model presented above perfectly illustrates the further possibilities for the development of robotic biomimetics in constructing robots inspired by rats. Qing Shi is one of the scientists who has significantly contributed to the advancement of robotic rats and to research on their social capabilities¹⁷. There are many potential future applications for advanced robotic rats, not only in studies of social interactions but also in data collection within rodent groups to gain a better understanding of their functioning and behaviors.

¹⁷ A list of articles published by the author can be found on his website at <https://sites.google.com/view/qingshi/publications?authuser=0> (accessed: 06/01/2023) (author's note).

Summary

The analysis of the article highlights the vast potential of robotic biomimetics, showcasing remarkable advancements in this field, particularly concerning the Waseda Rat robot designed by scientist Qing Shi and his collaborators. The conducted studies on the social interactions of WR-5 and its earlier versions with laboratory rats demonstrated that the robot can significantly influence not only the behavior of the animal but also the way it is treated by other group members. The indirect change in rodent behavior caused by the robot, observed during the experiments, represents a significant achievement in the analysis of the broad interactions between robots and animals. However, one cannot remain indifferent to the ethical dimension of the conducted research. Without undermining their undeniable scientific value, I would like to emphasize that the intended purpose of the experiments was to expose laboratory rats to chronic stress, resulting in induced depression and a devaluation of the individual's social standing. Referring to the passage on animal research ethics included in the introduction, I believe that, from an ethical perspective, experiments on animal models of mental illnesses involving the robot are harmful to the subjects of the research. Citing the five-step scale of interference with the animal's organism during laboratory experiments proposed by the National Ethics Committee for Animal Experiments in Poland, one can assume that the studies described in my article fall between the third and fourth levels. According to available reports, the interactions between the robot and the rats did not significantly interfere with the welfare of the test animals or cause permanent harm to their health or mental state. However, the experiments included elements of constant exposure to stress without the possibility of escape, defined as a fourth level of violation of the ethical rights of laboratory animals. Biomimetic robotics offers great opportunities not only in technology and mechanics but also for improving the living conditions of various species. Robots should be utilized in collecting data about living organisms to better understand their needs. Therefore, I believe that the knowledge and technological capabilities of scientists in the 21st century allow for actions that strive for the common good of both humans and animals.

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