# Development of a Rat-like Robot and Its Applications in Animal Behavior Research

## ラット形ロボットの開発とその動物行動研究への応用

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# ABSTRACT

The study of animal behavior has a long history and covers many fields, significantly influencing the progress of neuroscience, psychology, pharmacology, etc. In the study of animal behavior, the social behavior has drawn lots of attentions for completely different purposes. Social behavior refers to the actions that affect other individuals currently or in the future. It is the indicator of anxiety level and sociality. Meanwhile, recently there are many studies involve developing psychotropic drugs and clarifying the mechanism of mental disorder by using animal models of mental disorder (AMMD), due to the constantly growing number of patients suffering from mental disorder. AMMD are living experimental systems used to analyze brain-behavior relationships under controlled conditions, and they are used to represent phenotypes, such as behavior disorders or plastic changes in the brain, of the human patients suffering from mental disorders. In recent years, numerous attentions are attracted by the methods, in which the rats or mice are exposed to stress to create AMMD. Actually, in humans social stress is viewed as a major etiological factor in the development of mental disorder, including depression and anxiety. Social interaction (stressful) serves as an evolutionarily important source of stress, and one that is virtually ubiquitous among mammalian species.

Therefore, rat models of mental disorder (RMMD) can be created based on the social interactions between them. The assessment of the rat models can be achieved through several behavioral tests, such as the social interaction test (SIT), the open-field test (OFT), etc. Psychologically, in SIT the stress level of rats is generally scored based on the motion parameters (frequency of rearing / following, amount of movement, etc.).

However, the social interaction between real animals is hard to control and evaluate quantitatively. Since the behavior of one rat will influence that of the other, the scores of the treated rat may vary with partners.

As a solution approach, bio-inspired robots can be used to test different models. The use of reactive robots has opened new perspectives in the study of animal behaviors. However, many of these robots can only roughly mimic the behavior of animals. In particular, these devices in general are not well studied in the aspect of *interaction modeling* and *shape imitation*. Better shape imitation generally allows more realistic interaction between the robot and animals. Regarding interaction modeling, it is significantly important since most of the researches are involved with the analysis or control of animal behavior. Actually, interaction modeling helps to find the specific relationships in the robot-rat interaction. But the interaction between the robot and animal in existing experimental systems cannot be analyzed quantitatively.

In summary, the goal of this thesis is to develop a rat-like robot agent that is fully controllable in the social interaction with rats. To reach this goal the following aims must be fulfilled.

1) The first aim is to develop a mobile robot that has a shape similar to a real rat, and also has the capability to mimic typical actions of a rat. Considering the rich research experiences and fruits in biorobotics, the author proposes a new experimental system, in which the author replaces a real rat by the rat-like robot, in order to perform interaction experiments with another rat. The robot serves as not only the interaction partner but also the stimulus event.

2) The second aim is to develop a recognition system installed in the robot to recognize and analyze rat behavior automatically. The contributions of the recognition system are expected as the following two aspects: a) real-time recognition of rat behavior; b) adaptive behavior generation of the robot.

3) The last aim is to find the specific relationships between rat behavior and rat stress, robot behavior. This thesis proposes to clarify these relationships by using mathematical models derived from numerous experimental results. Based on the specific mathematical models, if the robot behavior is strictly controlled, the rat behavior can be determined, and the stress level of rats can be calculated as well, and vice versa. Thereby, the control and analysis of rat behavior can be achieved.

The contents of this thesis can be laid out by the following 7 chapters.

Chapter 1 introduces the research background, objectives, significance and potential research directions in the future. Afterwards, a novel methodology is described concisely. Finally, this chapter outlines the organization of this thesis.

Chapter 2 reveals that the complicated relationships among robot behavior, rat behavior and stress level of rats in robot-rat interaction can be represented by specific mathematical models. In this research, only the robot is considered as the unique stimuli that can change rat behavior in this system. Likewise, the robot is thought to be able to influence the stress level of rats by interacting with them. At first, the author proposed to derive the functional relationship between the behavior and stress level of rats based on previous research and numerous experimental results. The stress has significantly close influence in the mental disorder, so it is the focus of this thesis. According to previous research results, the stress level of rats can be represented by the linear combination of motion variables such as the amount of movement, the frequency of rearing, body grooming behaviors, the distance between rat subject and partner. Principal component analysis (PCA) is employed to specify the coefficients of each variable in the linear mathematical model. Likewise, linear discriminant analysis (LDA) is used to confirm the effectiveness of the specified linear mathematical model.

Chapter 3 introduces the design and development of three rat-like mobile robots. A quadruped walking robot called WR-2 was designed similarly with the same size as a mature rat. This robot moved at a very low speed and could not rotate as naturally as real rats. As an improvement, a wheel-legged robot called WR-3 endowed with higher moving speed and better imitation of rat behavior was developed. However, limited moving range of waist and neck of WR-3 caused linear bend posture, which is different with the curved bend posture of rats. Given this lack of a suitable experimental biomimetic robot platform, it is essential to develop a robot that can sufficiently imitate the behaviors of a rat. Building on the experiences gained from previous robot prototypes, to propose a multi-bendable body, which is capable of moving more steadily and bending more similarly as living rats, the improved robot called WR-4 was developed. WR-4 achieves to the bending posture as real rats due to the 6-bar linkage mechanism in the waist and 4-bar linkage mechanism in the neck.

Chapter 4 describes an automated video processing system to replace the traditional manual annotation, as well as to improve the adaptivity of the rat-like robot to autonomously interact with rats. The image processing based recognition system contributes to recognize rat behavior. The robot behavior is generated based on the recognized rat behavior to meet the

purpose of experiments. In general, the robot is able to generate agonistic, friendly and neutral behaviors respectively, to create agonistic, friendly and neutral relationships with rats accordingly. Namely, the robot could change its behavior corresponding to experimental purpose.

In Chapter 5, stress exposure experiments are conducted to create rat models of mental disorder by using WR-3 robot. The results confirmed the successful development of RMMD, which exhibited fewer activities and behaviors during mature period when exposed to a agonistic robot during immature period. Based on the experimental results, the coefficients of the linear function representing the stress level of rats described in Chapter 2 were determined. Likewise, this model was used to calculate the stress level of rats exposed to agonistic conspecifics. The results are confirmed to be similar to robot-rat interaction system. Furthermore, compared to rat-rat interaction, there is less variance of the results in robot-rat interaction, which suggests the latter has better reproducibility. Also the usefulness of the robot agent in the social interaction is confirmed.

In contrast to Chapter5, Chapter 6 introduces friendly interaction experiments conducted to create friendly relationship between rats and the WR-4 robot. The author used the linear mathematical model specified in Chapter 5 to calculate the stress level of rat subjects. The results show that the friendly interaction is able to reduce the stress of rats. Likewise, the author successfully proved the effectiveness of the robot-rat interaction by comparing with the results from friendly interaction conducted between real rats. In the final of this chapter, the author discussed the results of Chapter 5 and Chapter 6 comprehensively. Therefore, based on the interaction modeling, the friendly or agonistic relationship with rats could be created at will.

Chapter 7 introduces the conclusions of the whole thesis and the further possible research direction from this research.

In conclusion, this thesis demonstrates an intelligent robot agent that can be used to interact with rats in the social interaction. Specifically, the development of a robot with better imitation of rat shape and behavior, robot-rat interaction modeling and demonstration experiments were narrated. Finally, the author argued that the control of the robot allows creating friendly or agonistic relationship with rats based on the interaction modeling.

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# LIST OF ABBREVIATIONS

| | |
|---|---|
| AMMD | animal model of mental disorder |
| ANN | artificial neural network |
| CSE | compulsory stress exposure |
| EPMT | elevated-plus maze test |
| FA | factor analysis |
| $f_b{}^1$ | rat behavior |
| $f_b{}^2$ | recognized rat behavior |
| $f_b{}^3$ | updated robot behavior |
| $f(f_b{}^2)$ | function to represent the stress level of rats |
| ISE | interactive stress exposure |
| LC | linear classifier |
| LDA | linear discriminant analysis |
| LLSF | linear least square fitting |
| MCU | microcontroller unit |
| MEMS | micro-electro-mechanical system |
| PCA | principal components analysis |
| RMMD | rat model of mental disorder |
| $S$ | stress level of rats |
| SMA | shape memory alloys |
| TMT | T-maze test |
| USM | ultrasonic motor |
| ZMP | zero moment point |

| | |
|---|---|
| $X_1$ | behavior discriminate vector |
| $X_2$ | motion parameter |
| $X_3$ | generated motion pattern |
| $\varphi(S, f_b{}^2)$ | function to represent the behavior generation of robots |
| $\psi(f_b{}^3)$ | function to represent the behavior generation of rats |

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# Chapter 1

# Introduction

## 1.1 Research Background

### 1.1.1 The Study of Animal Behavior

The study of animal behavior started almost 200 years ago and spread all over the world. It covers many fields, neuroscience, psychology, pharmacology, ethology, etc. Neuroscience is the scientific study of the nervous system. Traditionally, neuroscience has been seen as a branch of biology. Based on the subject and scale of the system in examination as well as distinct experimental or curricular approaches, neuroscience education and research activities can be categorized several branches. As one of the major branches, behavioral neuroscience , also known as biological psychology, biopsychology, or psychobiology is the application of the principles of biology (in particular neurobiology), to the study of physiological, genetic, and developmental mechanisms of behavior in human and non-human animals. Most typically, experiments in behavioral neuroscience involve non-human animal models (such as rats and mice, and non-human primates) which have implications for better understanding of human pathology and therefore contribute to evidence-based practice.

In many cases, humans may serve as experimental subjects in behavioral neuroscience experiments; however, a great deal of the experimental literature in behavioral neuroscience comes from the study of non-human species, most frequently rats, mice, and monkeys. As a result, a critical assumption in behavioral neuroscience is that organisms share biological and

Figure 1.1 The interactions and relationships between chimpanzees

behavioral similarities, enough to permit extrapolations across species. Therefore, the study of animal behavior significantly contributes to the understanding of human behavior.

In fact, animal behavior is the bridge between the molecular and physiological aspects of biology and the ecological. Behavior is the link between organisms and environment and between the nervous system, and the ecosystem. Behavior is one of the most important properties of animal life. Behavior plays a critical role in biological adaptations. Behavior is how we humans define our own lives. Behavior is that part of an organism by which it interacts with its environment. Behavior is as much a part of an organisms as its coat, wings etc. The beauty of an animal includes its behavioral attributes.

In the study of behavior, the social interactions between individuals have drawn lots of attention for completely different purposes. For instance, in [1] the peer interactions of 6 infant chimpanzees (Pan troglodytes) ranging in age from 18 to 50 months were observed in a seminatural context (Figure 1.1). The results indicate that a number of factors may influence the peer affiliations of infant chimpanzees, including the age of the infant and the mother's social relationships. Mirror neuron is a neuron that fires both when an animal acts and when the animal observes the same action performed by another [2]. The first animal in which mirror neurons have been studied individually is the macaque monkey (Figure 1.2). These mirror

Figure 1.2 Macaca monkeys for the research of mirror neurons related to the imitation and language acquisition



Figure 1.3 Rat models of mental disorder

neurons may be important for understanding the actions of other people, and for learning new skills by imitation. To develop psychotropic drugs and clarify the mechanism of mental disorder, many animal (rat, mice, etc.) models of mental disorder (AMMD) have been created. The social interactions between these models [3] are considered as the main validity indices. Modeling of human mental disorders in animals is extremely challenging given the subjective nature of many symptoms, the lack of biomarkers and objective diagnostic tests, and the early state of the relevant neurobiology and genetics. Nonetheless, progress in understanding pathophysiology and in treatment development would benefit greatly from improved animal models.

### 1.1.2 Brief History of Mental Disorder

In recent years, with the tremendous development of scientific technologies, the communications among human, thing and information based on the progress of rapid means of transportation, and information and communication technologies, are globally activated, resulting in a completely changed world. Furthermore, the life style of us has been greatly changed. For example, the spread of home electrical appliances such as the air conditioner and washing machine helps to improve living convenience and expand living space. Besides, the invention of mobile phones and internet makes information exchange significantly easier and quicker than before. Actually, it seems impossible to count all the "positive parts" of the changes brought by the development of scientific technologies.

However, there is no possibility that all the changes brought by the rapid progress of scientific technologies are positive. The increasing social problems caused gradually by the polluted environment, bioethical issues, etc., are considered as "negative parts" of the changes brought by scientific technologies. As the bad influences caused by these issues resulted from the "negative parts" of the changes cannot be ignored, the solutions are urgently required. The words of Stress Society can be heard frequently these days, which is attributable to the increasing number of people complaining of the stress in recent years. The increased stress is rightly one of the "negative parts" of the rapid changes in society.

The term stress originally means pressure, strain, distress, etc. In the 1920s and 1930s, the term was occasionally being used in psychological circles to refer to a mental strain or unwelcome happening, and by advocates of holistic medicine to refer to a harmful environmental
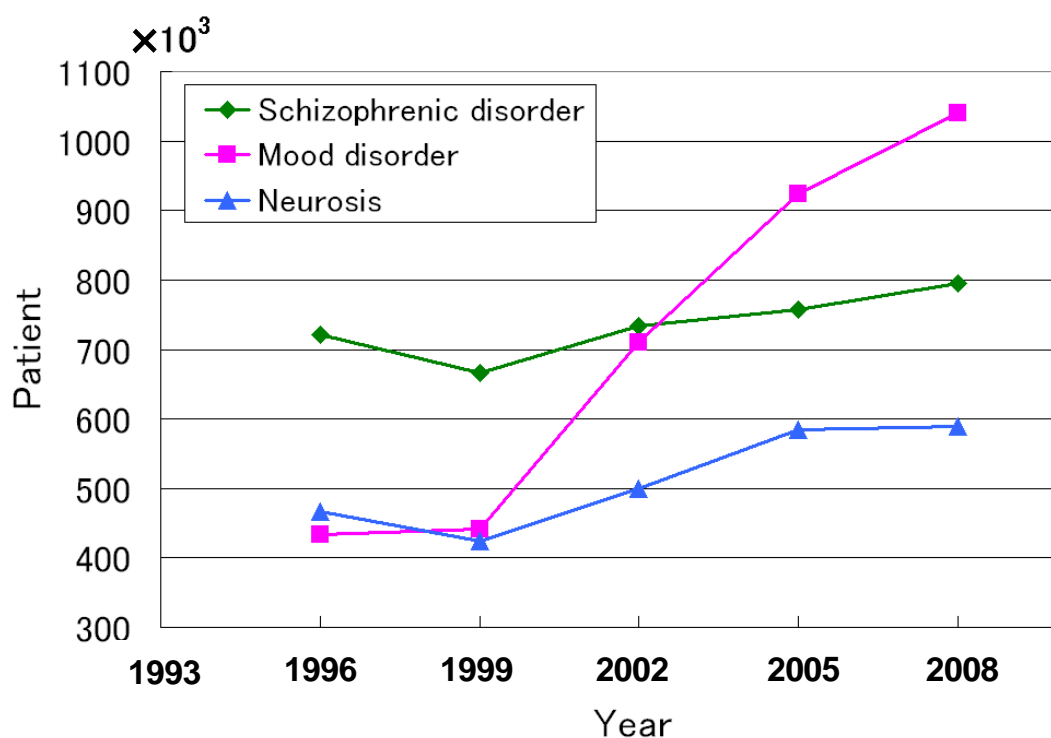
Figure 1.4 Increasing number of the patients suffering from mental disease

agent that could cause illness. The novel usage arose out of Selye's 1930s experiments. He started to use the term to refer not just to the agent but to the state of the organism as it responded and adapted to the environment [4], [5]. His theories of a universal non-specific stress response attracted great interest and contention in academic physiology and he undertook extensive research programs and publication efforts. Furthermore, in the late of 1960s, in psychology field, many researchers studied on the life stress related to the associations between the physical and mental disorder, and the changes in living environment or life events. As an opportunity, the research to clarify the psychosocial factors related to the stress becomes more active. In 1967, psychiatrists Holmes and Rahe examined the medical records of over 5,000 medical patients as a way to determine whether stressful events might cause illnesses. Their results were published as the Social Readjustment Rating Scale [5], known more commonly as the Holmes and Rahe Stress Scale. Lazarus and Folkman suggested in 1984 that stress can be thought of as resulting from an "imbalance between demands and resources" or as occurring when "pressure exceeds one's perceived ability to cope". Stress management was developed and premised on the idea that stress is not a direct response to a stressor but rather one's resources and ability to cope mediate the stress response and are amenable to change, thus allowing stress to be controllable [6]. As above-mentioned, there is a long history of the

research on stress. Recent research results have clarified gradually that the stress is considered as the incentive of various diseases and aging problems. For example, the mental disorder causing terrible social problems these days is mainly induced by the stress. Actually, the number of patients suffering from mental disorder has been constantly growing ( Figure 1.4) [7]. A mental disorder or mental illness is a psychological or behavioral pattern generally associated with subjective distress or disability that occurs in an individual, and which is not a part of normal development or culture. Such a disorder may consist of a combination of affective, behavioral, cognitive and perceptual components. The recognition and understanding of mental health conditions have changed over time and across cultures, and there are still variations in the definition, assessment, and classification of mental disorders, although standard guideline criteria are widely accepted. For example, mental disorder had been considered as spiritual or moral issues till 19th century (Figure 1.5), and the people suffering from mental disorder were treated by pastors following the rules of religion. In fact, until recently, some people still strongly argue that affective, behavioral, cognitive and perceptual abnormalities should not be expressed in biological perspective. Thus it is considered as significant progress that these mental disorders were separated from religious issues. Furthermore, a new medical



Figure 1.5 Eight women representing prominent mental diagnoses in the 19th century

specialty called psychiatry [8] devoted to the study and treatment of mental disorders was prompted to emerge. Psychiatric research is, by its very nature, interdisciplinary. It combines social, biological and psychological perspectives to understand the nature and treatment of mental disorders. Freud [9], an Austrian neurologist, has contributed a lot in this field. Freud is best known for his theories of the unconscious mind and the mechanism of repression, and for creating the clinical method of psychoanalysis for investigating the mind and treating psychopathology through dialogue between a patient (or "analysand") and a psychoanalyst [10]. Skinner invented the operant conditioning chamber, to measure responses of organisms (most often, rats and pigeons) and their orderly interactions with the environment. Skinner innovated his own philosophy of science called radical behaviorism [11].

Psychopathology in non-human primates has been studied since the mid-20th century. Over 20 behavioral patterns in captive chimpanzees have been documented as (statistically) abnormal for frequency, severity or oddness—some of which have also been observed in the wild. Captive great apes show gross behavioral abnormalities such as stereotypy of movements, self-mutilation, disturbed emotional reactions (mainly fear or aggression) towards companions, lack of species-typical communications, and generalized learned helplessness. In some cases such behaviors are hypothesized to be equivalent to symptoms associated with psychiatric disorders in humans such as depression, anxiety disorders, eating disorders and post-traumatic stress disorder. Concepts of antisocial, borderline and schizoid personality disorders have also been applied to non-human great apes.



Figure 1.6  Social stress due to bad human relationship

(a) Genetic manipulation          (b) Stressful environment

Figure 1.7 Method of developing animal models of mental disorder

The risk of anthropomorphism is often raised with regard to such comparisons, and assessment of non-human animals cannot incorporate evidence from linguistic communication. However, available evidence may range from nonverbal behaviors—including physiological responses and homologous facial displays and acoustic utterances—to neurochemical studies. It is pointed out that human psychiatric classification is often based on statistical description and judgment of behaviors (especially when speech or language is impaired) and that the use of verbal self-report is itself problematic and unreliable.

## 1.1.3 Mental Disorder Treatment and Research by using AMMD

As described in the preceding section, the number of patients suffering from mental disorder has been increasing. Especially the number of patients suffering from mood disorder is in a rapid growth, and it is mainly induced by the social stress due to bad human relationship from work, study, everyday life, etc. (Figure 1.6). To deal with such a serious situation, in recent medical research, increasing attention has been directed to mental disorder therapy and psychotropic drugs development. However, as the psychotropic drugs newly developed may have strong side effects, it is quite essential to establish an in vivo assay system to evaluate the dose and effectiveness of the drugs. Due to psychologically sophisticated mind, as well as the

difficulty to collect data and ethical issues [12], it is difficult to directly use human beings as experimental subjects for research on mental disorder. Consequently, AMMD [13–15] have

been used to clarify the mechanisms of mental disorder and produce new psychotropic drugs. These animal models are living animals that suffer from phonotypical mental disorders. In behavioral neurosciences, such as neurobiology and biopsychology, animal models make it possible to investigate brain‑behavior relations, with the aim of gaining insight into normal and abnormal human behavior and its underlying neuronal and neuroendocrinological processes. As shown in Figure 1.7, these animal models are specifically created by genetic manipulation, selective breeding for extremes in a particular behavioral phenotype, surgical operation on the brain, psychotropic drugs and stressful environment [15], [16]. In addition, combination of these strategies, for example, superposing environmental influences on genetically-modified or selectively-bred animals is employed.

This thesis mainly discusses the development of AMMD through environmental manipulations. Exposure to a stimulating, enriched environment exerts a profound effect on brain structure and function, enhancing neurogenesis, gliogenesis, synaptogenesis and angiogenesis, stimulating the activity of several neurotransmitter systems and increasing the gene expression of growth factors, such as Nerve Growth Factor and Brain derived Growth Factor [17] and [18]. It also improves memory function in several learning tasks [17] and [19].

In general, rats or mice are used for such AMMD owing to their genetic consistency and reaction to drug treatment, which is similar to humans. Although other species, notably primates, also serve as subjects of laboratory investigation of social stress effects, their social and stress-related behaviors are more commonly observed under seminatural conditions, or in the wild. In humans, social stress is viewed as a major etiological factor in the development of mental disorder [20], including depression and anxiety. Social interaction (stressful) serves as an evolutionarily important source of stress, and one that is virtually ubiquitous among mammalian species. [21] Shows that agonistic behavior is the major mechanism by which social experience is regarded as producing stress. For laboratory mice and rats, the most commonly used subjects of social stress laboratory research, agonistic behavior is a very obvious and salient component of most social grouping studies. It may be measured directly, in terms of fighting within each specific male dyad, or indirectly, in terms of wounds on the combatants. Therefore, rat models of mental disorder (RMMD) can be created based on the social interactions between them.
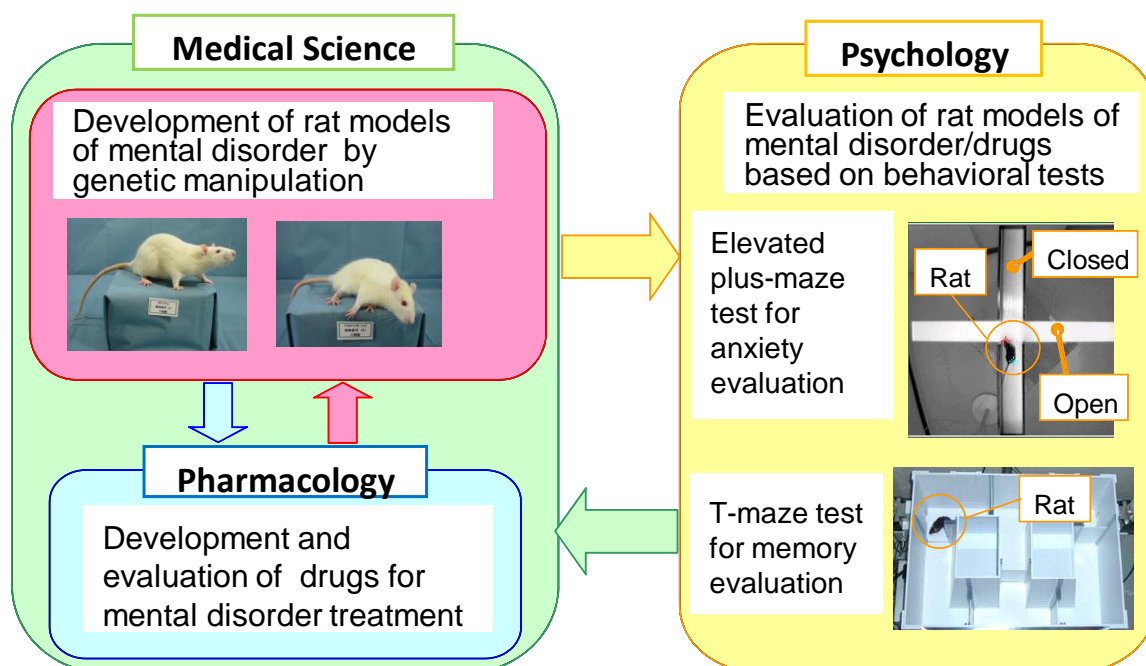
Figure 1.8 In vivo assay system
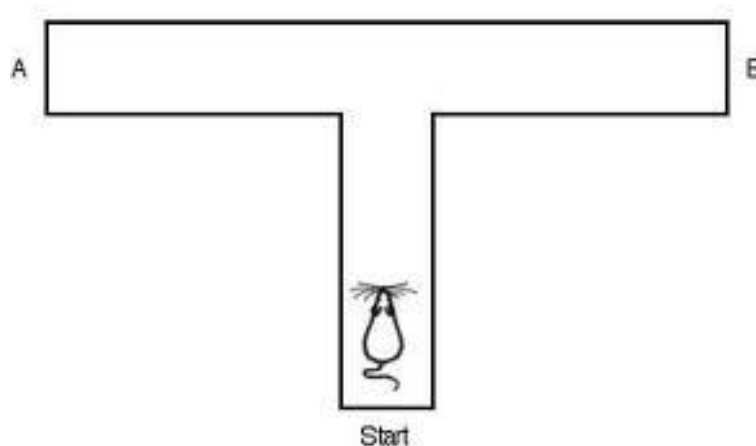


Figure 1.9 T-maze test

The validity and reliability of this aspect of animal models can be evaluated by making use of procedures and concepts from testing psychology. It involves the measurement of behavioral characteristics of the model. Normally, a battery of psychological tests is used to assess behavior, where psychological test refers to careful observation in a standardized experimental setting [22]. Testing then refers to the process by which these observations are collected [23]. The assessment of the rat models can be achieved through several behavioral tests,
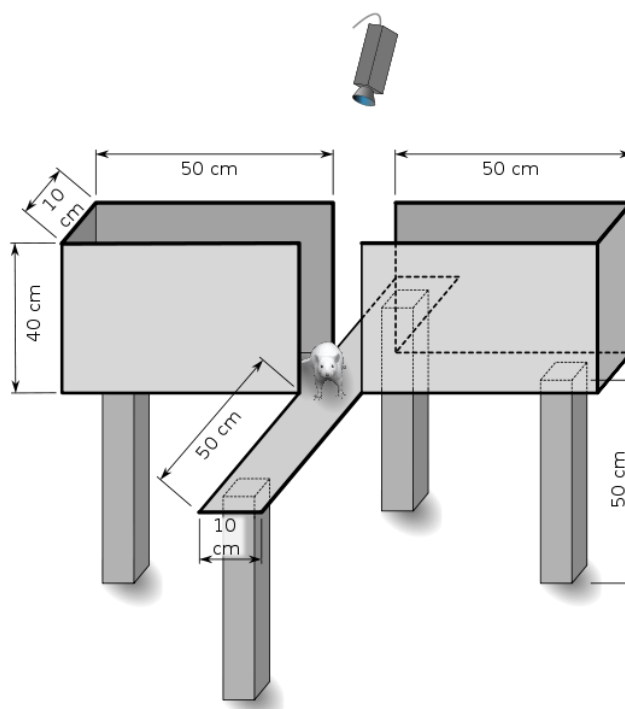
Figure 1.10 Elevated plus-maze

such as the social interaction test (SIT) [24], the open-field test (OFT) [25], the elevated plus-maze test (EPMT) [26], the T-maze test (TMT) [27], etc. Since the social stress is the main factor for the development of RMMD, the stress level of the animal models should be assessed to evaluate the validity. As an example, a typical in vivo assay system can be illustrated in Figure 1.8.

A shown in Figure 1.9, the T-maze is shaped like a T. The animal subject of TMT starts at the base of the T. A reward may be placed in one arm of the maze, or different rewards may be placed in each arm. The rat walks forward and chooses the left or right arm of the maze. The TMT can be used to study a variety of questions in learning and cognition including discrimination, and spatial and nonspatial navigation.

The EPMT for testing a rodent model of anxiety that is used as a screening test for putative anxiolytic or anxiogenic compounds and as a general research tool in neurobiological anxiety research. As shown in Figure 1.10, the test setting consists of a plus-shaped apparatus with two open and two enclosed arms, each with an open roof, elevated 40–70 cm from the floor. The model is based on rodents' aversion of open spaces.

The OFT is designed to measure behavioral responses such as locomotor activity, hyper-activity, and exploratory behaviors in laboratory animals (rats or mice). This test is particularly useful in evaluating the effects of anxiolytic and anxiogenic drugs, locomotor responses to drug and as well as behavioral responses to novelty. The open field area generally consists of an empty and bright square (or circular) arena, surrounded by walls to prevent animal from escaping (Figure 1.11). The animal is usually placed in the center of the arena and its behavior recorded over a chosen period (from 3 to 15 min). The OFT task approaches the conflict between the innate fear that rodents have of the central area of a novel or brightly lit open field versus their desire to explore new environments. When anxious, the natural tendency of rodents is to prefer staying closed to the walls (thigmotaxis).

The SIT was developed more than 30 years ago [28] as the first animal test of anxiety that endeavoured to use ethologically relevant sources of anxiety, and to use a natural form of behavior as the dependent measure. The SIT is normally conducted on two male rats in an open-field (Figure 1.11). It, therefore, avoided the use of food or water deprivation and electric shock, and did not require extensive training of the animal. The dependent variable is the time spent by pairs of male rats in social interaction (e.g., mounting, sniffing, following or grooming the partner as shown in Figure 1.12). Because the behavior of one rat influences that of the other, it is important that the pair of rats is treated as a unit, and only one score for the pair is used. Thus, it is possible to use a total or mean score for the pair, or if only one rat is treated (as is often the case for central drug administration), then only the scores of the treated rat should be used. It is a false inflation to use separate scores for each member of the pair, as if they were two independent individuals. An increase in social interaction, without a concomitant increase in motor activity, is indicative of an anxiolytic effect, whereas a specific decrease in social interaction indicates an anxiogenic effect [29]. Likewise, the social interaction (e.g., activity) is considered as one of the main indices of human mental disorder symptoms [30]. In this thesis, the author will mainly discuss this kind of behavioral test to evaluate the RMMD.

Figure 1.11 Open-field
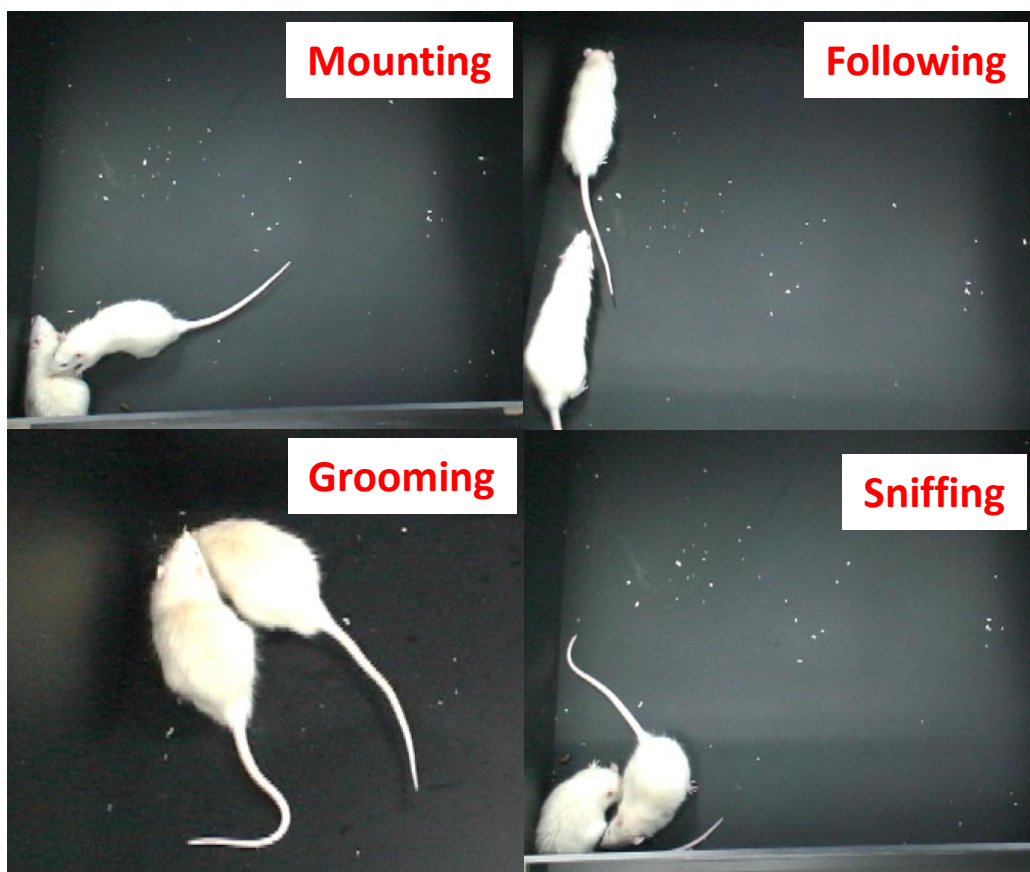


Figure 1.12 Typical social interactions between two rats in SIT

# 1.2 Motivation and Research Objectives

## 1.2.1 Motivation

In general, interaction experiments between rats are conducted for research and treatment of human mental disorders. As described in the former section, there are already rich research
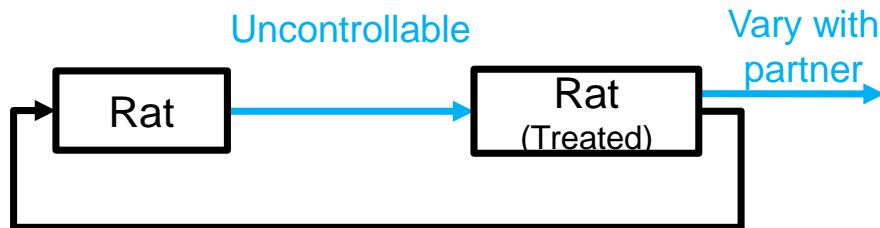
Figure 1.13 Experiments between living rats
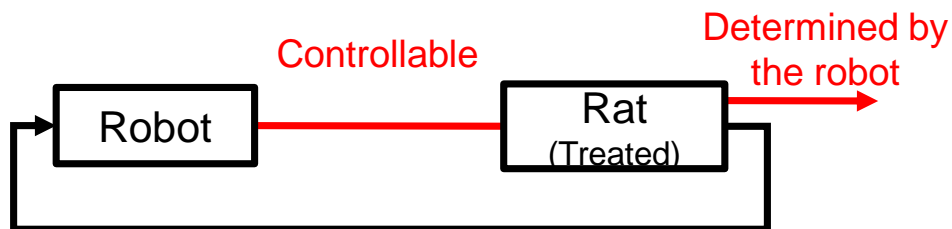
Figure 1.14 Robot-based animal experiments

experiences on the development of RMMD based on the results of social interactions. In addition, social interaction serves as the evaluation index of these animal models based on the behavioral test (e.g., SIT). However, as shown in Figure 1.13, the conventional animal experimental conditions are difficult to control. Since the behavior of one rat will influence that of the other, the scores of the treated rat may vary with partners. Therefore, the real animal experimental system is hard to control and evaluate quantitatively.

As a solution approach, bio-inspired robots can be used to test different models. Robots offer two distinct advantages over the usage of real animals in such studies. First, the exact behavior of the robot is controllable and therefore its actions are clearly defined. Second, compared to an animal the robot allows obtaining a wide range of quantitative data (actuator states, sensor input etc.). Bio-inspired robots are playing an increasingly important role as a link between the worlds of biology and engineering. The new, multidisciplinary field of biorobotics provides tools for biologists studying animal behavior and test beds for the study

and evaluation of biological algorithms for potential engineering applications [31]. Besides, robots are not virtual, but physical entities, and as such they interact with a real environment. This quality, that no simulation or mathematical model will ever have, allows their integration in experiments with real animals [32]. Therefore, a novel method integrated robot technology for animal experiments is shown in Figure 1.14. The advantages of this method lie in better controllability and reproducibility. However, the advantages are significantly restricted to the motion performance and intelligence of the biorobotics.

Most recently, the use of reactive robots has opened new perspectives in the study of animal behaviors. These new devices are able to adapt their behaviors to the behaviors of the animals they are interacting with. Varying the rules of interaction in the robot and observing the changes in the behaviors of the animals is an interesting solution to systematically explore the social repertoire of the species under study. Moreover, these devices proved to be able to control the behaviors of the animals to some degree. For instance, the InsBot robot [33] (Figure 1.15) can discriminate cockroaches, other robots, environment boundaries and shelters. It has also three means of communication for monitoring, logging, supervision of biological experiment and detecting other robots in short range. [34] presented a honeybee robot capable of reproducing very realistic dances and reacts on its environment (Figure 1.16). This robot is promising to enable biologist to conduct complex biological experiments on the honeybee dance communication system. A chicken robot called PoulBot [35] (Figure 1.17) is able to autonomously record experimental video and audio data, to detect displacement of chicks and robots, to detect their calling activity and to provide robots with these data. The robot can be accepted by chick groups using the filial imprinting learning process modulated by the patterns that are displayed by the robot and its sound emission. The tracking system with high performance makes it possible to quantify the strength of the imprinting and the level of leadership the robot has on the chicks. Likewise, it serves to quantify both the individual and the group behavior and to study the impact of the individual behavioral parameters on the collective level. As shown in Figure 1.18, Psikharpax project held in France [36] aims at designing an artificial rat able to "survive" in a laboratory populated by humans and other robots. The unique of Psikharpax lies on the following. First, it draws inspiration from a vertebrate instead of an invertebrate. Second, it aims at designing both biomimetic sensors and control architectures. Third, because it capitalizes on a dedicated robotic platform, it will integrate a variety of sensors, actuators and control systems making it possible to assess its capacities in much
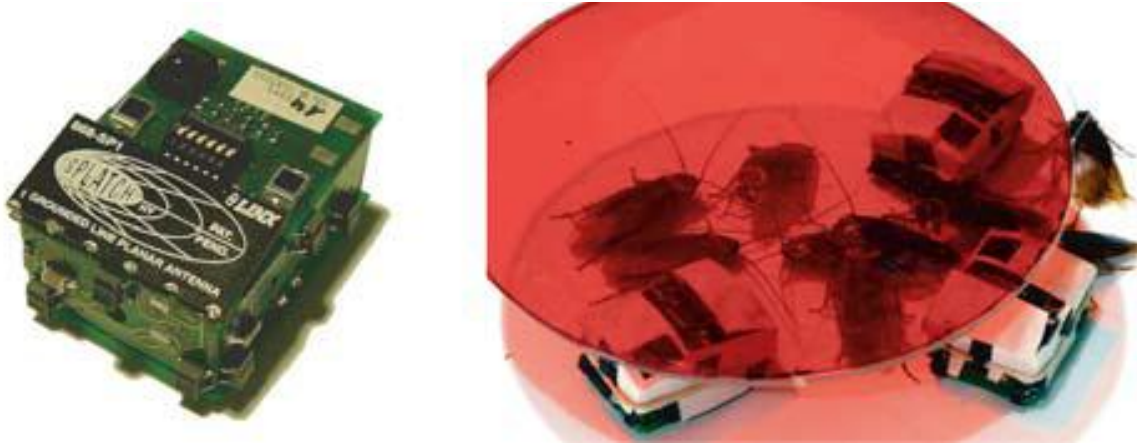
Figure 1.15 Left: InsBot without cover. Right: InsBot with their convers aggregated with cockroaches under a shelter
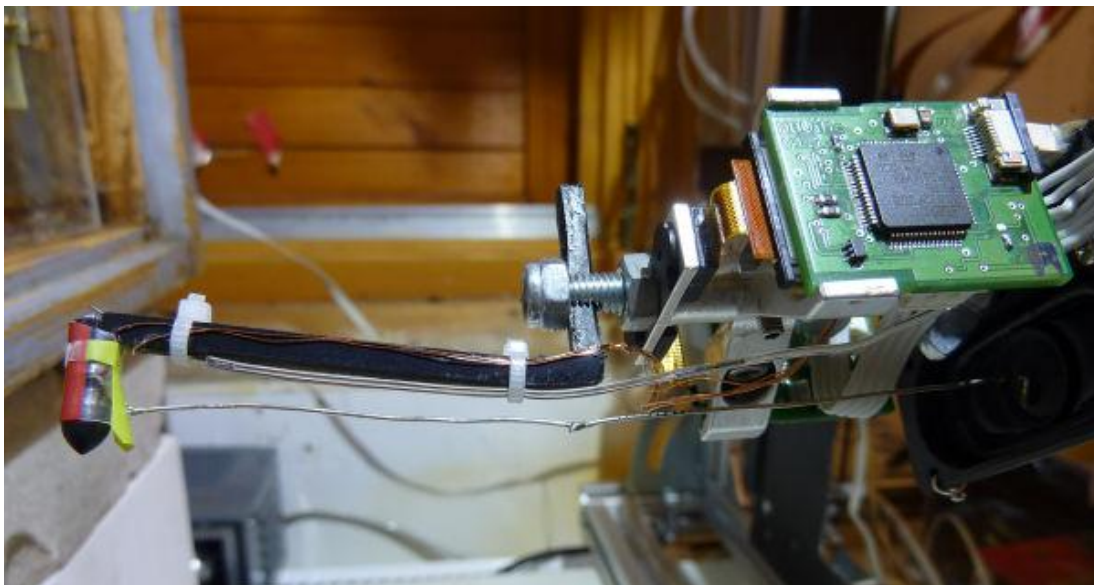


Figure 1.16 Close up of the central rod at whose end the robotic bee body is attached. It integrates a temperature sensor and a heating resistor. A small canula is used to deliver small amounts of sugar solution to the body's head

Figure 1.17 The PoulBot robot with an activated sample color pattern. The modules are, from base to top: a base, a Plexiglas bumper, a color pattern module, an extra IR sensors and a top makers board.



Figure 1.18 The Psikharpax robot equipped with three sets of allothetic sensors: a two-eyed visual system, an auditory system calling upon two electronic cochleas, and a haptic system made of 32 whiskers on each side of its head.
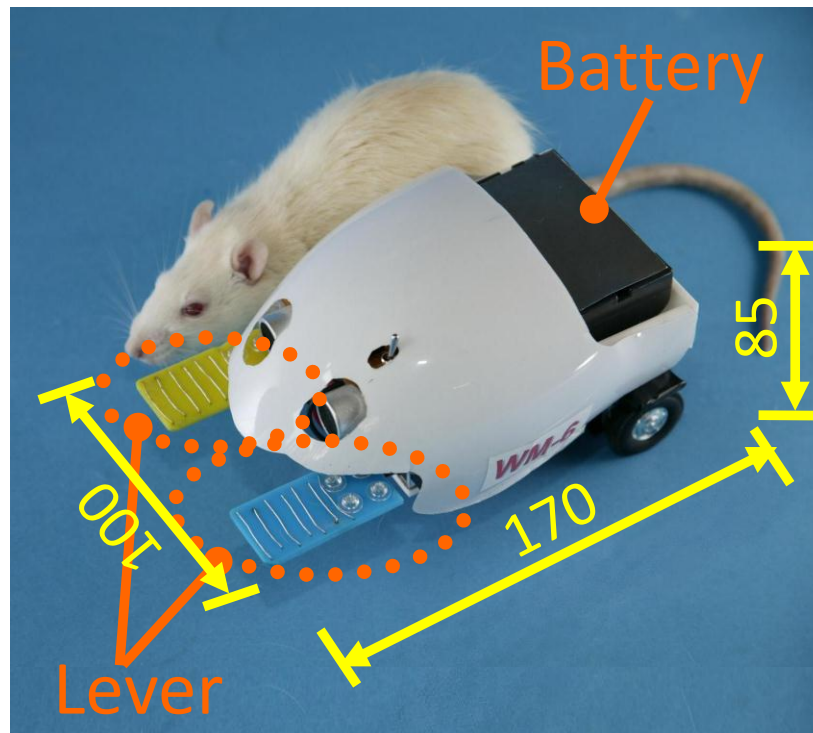
Figure 1.19 WM-6 robot developed to interact with rats. It has two levers to interact with the rats

more challenging circumstances than those that characterize seemingly comparable robotic approaches.

As the previous studies of this project, [28], [29] investigated the basic factors for a symbiosis between humans and robots through interaction experiments between a rat and a robot. An intelligent robot called WM-6 was developed to interact with rats in the experiments. The following three results were obtained.

- The rats were able to recognize the functions of the robot and their needs could be satisfied by using the robot. This is a symbiotic relationship.
- The rat was able to live symbiotically with the robot for 24 hours. Therefore, it was unlikely that the rat suffered severe stress or was afraid of the robot.
- The possibility that a robot could control a rat was confirmed. However, it was possible that the rat suffered severe stress.

Consequently, the robot was able to both live with the rat symbiotically and control the rat by changing its behavior. This paper then confirmed that a relationship between a rat and a robot depended on robot's behavior strategy. It was first step to clarify the basic factors for the symbiotic relationship between them. The project is now investigating possibility a robot teaches rats how to use its functions.

Regarding the current research, the typical characteristics of the above-mentioned bio-inspired robots can be concluded as below.

Table 1.1 Comparison between several bio-inspired robots for interaction with animals

| Characteristics | Bio-inspired robot developed to interact with animals | | | | |
| --- | --- | --- | --- | --- | --- |
| | WM-6 | Psikharpax | PoulBot | Honeybee | InsBot |
| Behavioral Imitation | ▲ | ▲ | ▲ | ▲ | ▲ |
| Interaction Modeling | ✕ | ✕ | ▲ | ✕ | ✕ |
| Cognition | ▲ | ● | ● | ● | ▲ |
| Shape Imitation | ✕ | ▲ | ✕ | ✕ | ✕ |

※ ●: Superior performance ▲: General performance ✕: Poor performance

Most of the bio-inspired robots listed in Table 1.1 are endowed with excellent cognitive capabilities. However, all of them can only roughly mimic the behavior of animals. In particular, these devices in general are not well studied in the aspect of *interaction modeling* and *shape imitation*. The importance of shape imitation is involved with the influence in the interaction of the robot and animals to some degree as narrated in [39] though, it depends on the research objective and application as well. For instance, the sound emission of PoulBot serves to draw the interest of chicks. Regarding interaction modeling, it is significantly important since most of the researches involve with the analysis or control of animal behavior. Actually, the interaction between the robot and animal in existing experimental systems cannot be analyzed quantitatively. But the interaction modeling helps to find the specific relationships in the robot-rat interaction.

## 1.2.2 Problem Statements

As described previously, the main contribution of this thesis involves the improvement of conventional interaction experiments between animals. Below are the main problems of conventional experiments and related previous work.

1) The social interaction experiments between real rats does not have enough reproducibility due to individual differences of the rats used in the experiment [28]. In fact, the behavior of one rat will influence that of the other, and then the scores of the treated rat may vary with partners. Therefore, experimental system between real animals is hard to control and evaluate quantitatively. An earlier version robot called WM-6 for this study solved the problems to some degree, further improvement is needed due to the lack of several performances listed in Table 1.1.

2) In conventional animal experiments, the behavioral measures are mainly performed visually by trained observers, yielding significant measure errors due to individual differences. In addition, the measurement of animal behaviors is time consuming and not readily compatible with experiments requiring large groups of animals. Therefore, similar to other bio-inspired robotic system, the recognition system is necessary as well.

3) By far, the stress level of rats in the social interaction is generally scored based on the motion parameters (frequency of rearing, following, amount of movement, etc.). Some experiments were conducted to seek the relationship between behavior and stress in animal models [11-14], [40], as well as how the environmental factors (refer to events and stimuli that change behavior) influenced behaviors of animal models [41–44]. However, these relationships are not specific, let alone standard. Regarding different researchers, the assessment criteria of rat stress are not uniform, or even inconsistent, causing different results in similar experiments. In the view of robot-animal experimental system, such relationship is mainly involved with the robot and animals. Several bio-inspired robots, such as PoulBot, InsBot, Honeybee, etc., made attempts to find the relationship between robots and animals. Nevertheless, most of them are mainly based on qualitative analysis.

The conventional methodology receives many criticisms of its effectiveness because of these disadvantages. The motivation of this research is to propose new methodology to solve these limitations.

### 1.2.3 Research Objective

According to the preceding discussion, the goal of this thesis is to develop a rat-like robot agent that is fully controllable in the social interaction with rats. To reach this goal the following objectives must be fulfilled.

1) Considering the rich research experiences and fruits in biorobotics, the author proposes a new experimental system, in which the author replaces a real rat by a bio-inspired robot, in order to perform interaction experiments with another rat (Figure 1.20). The robot serves as not only the interaction partner but also the environment. As a requirement to do successful experiments, the shape and movement capabilities of the robot should be designed similarly to a real rat [39]. Therefore another research objective is confirmed as the development of a rat-inspired mobile robot that has a shape similar to a real rat, and also has the capability to mimic typical actions of a rat during experiments.

2) To recognize and analyze rat behavior automatically, the robot is expected to be endowed with a recognition system based on image processing and classification techniques. The goal of the recognition system is expected as the following two aspects: a) recognition of rat behavior; b) adaptive behavior generation for the robot to interact with rats autonomously.

3) In the novel robot-rat interaction, the author attempts to find the general and quantitative characteristics between rat behavior and stress level of rats, as well as how the robot behavior affects rat behavior. If these two kinds of relationships are determined, the relationship between rat stress and robot behavior could be specified quantitatively. The author aims to clarify these relationships by using mathematical models derived from numerous experimental results. Based on the specific mathematical models, if the robot behavior is strictly controlled, the stress level of rats can be determined, and vice versa. Thereby the control and analysis of rat behavior can be achieved. As the stress has significantly close influence in the mental disorder, so it is the focus of this thesis. Currently, the stress level of rats can be determined based on the relationship with rat behavior.
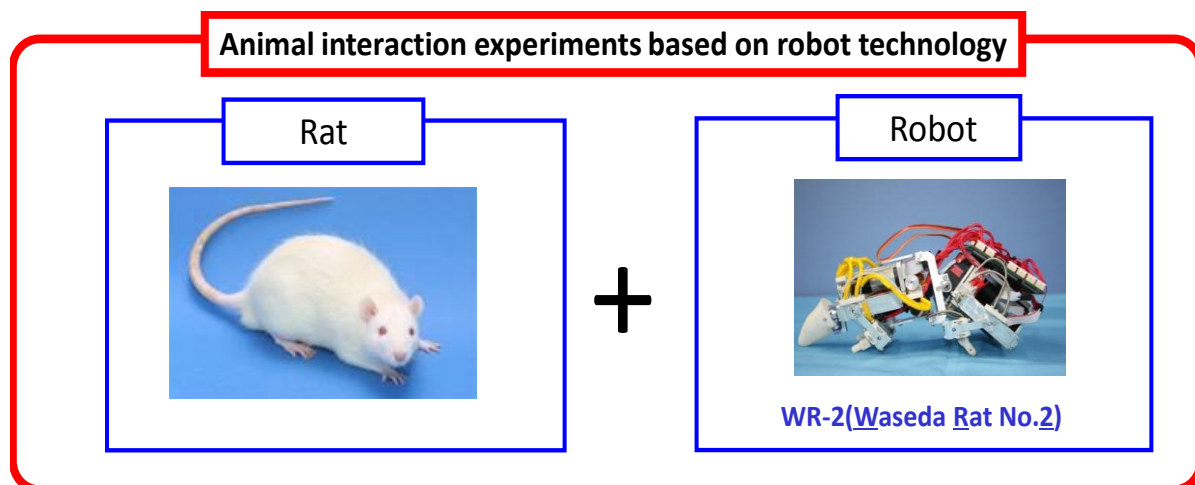
Figure 1.20 A new animal interaction experimental system for with integration of psychology and robotic technology
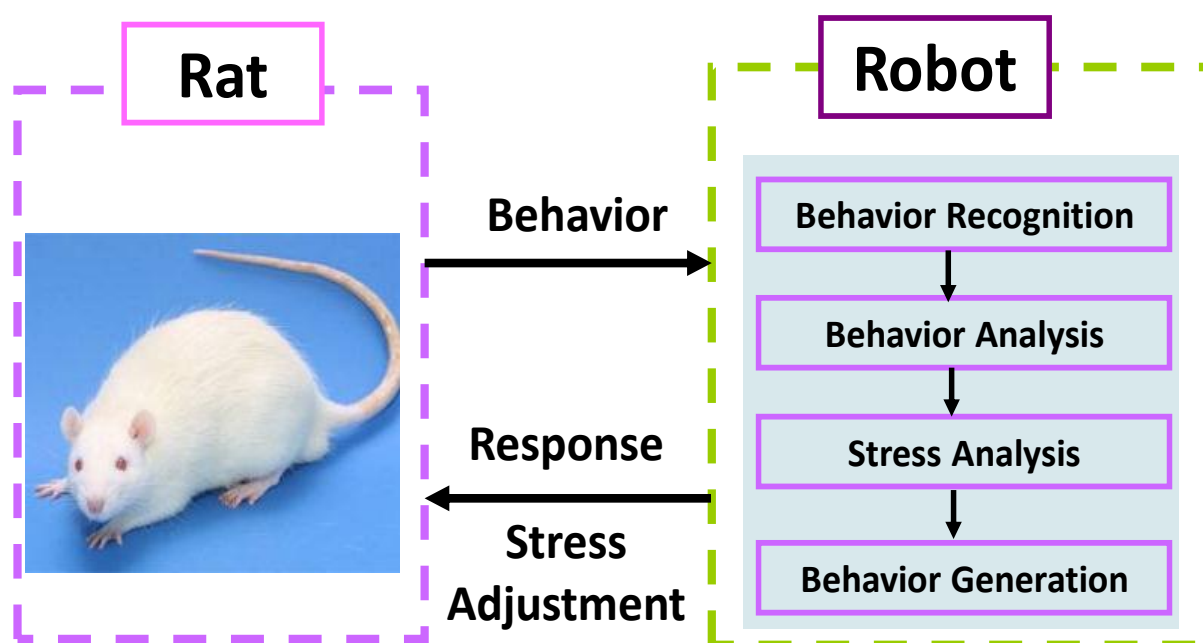


Figure 1.21 The analysis and adjustment of rat stress in a novel experimental system involved with robot technology

In summary, the goal of this thesis is to build a novel experimental system for the robot-rat interaction to analyze and control the stress level of rats. (Figure 1.21). In the future, this newly developed experimental system using rat-like robot is expected to analyze and adjust the stress of rats (e.g., perform attack behaviors to rats to create RMMD, interact with rats in a
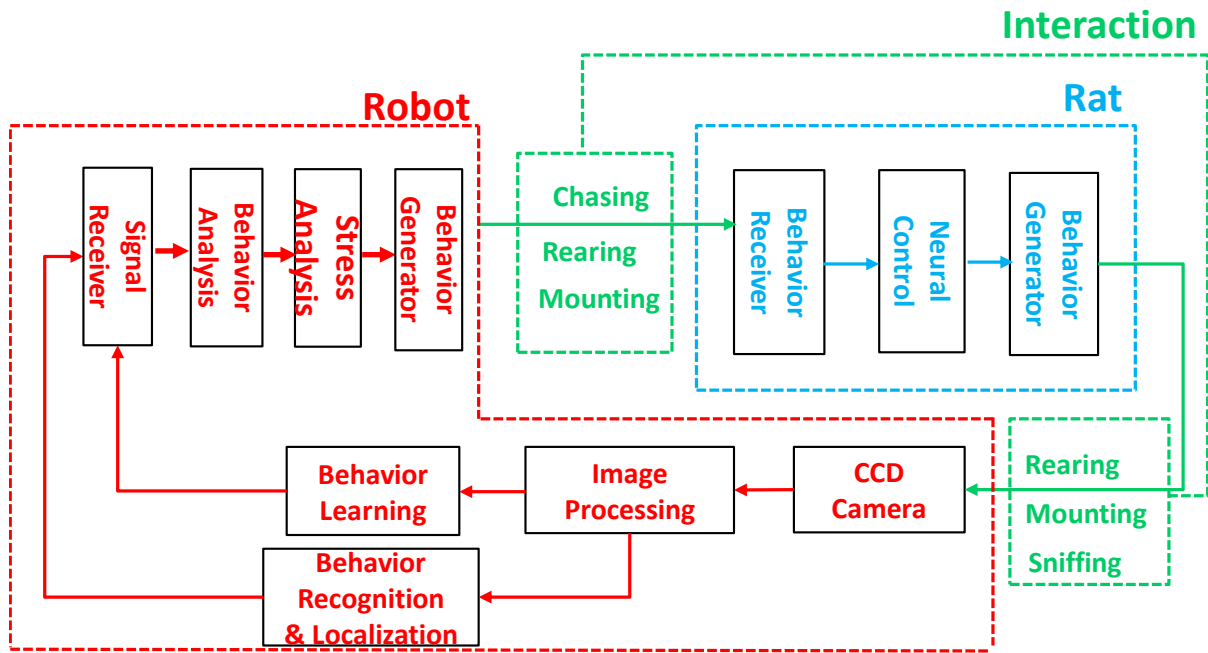
Figure 1.22 Overview of the whole system

friendly way to improve their anti-anxiety, i.e. to decrease the stress level of rats ) in realistic psychological and pharmacological application for mental disorder treatment.

# 1.3 Methodology

### 1.3.1 Reasons to Select Rats as Experimental Subjects

Rats are commonly employed as animal subjects in contemporary medical research, and general acceptance of the white rat as an animal research subject has increased in synchrony with an increased appreciation of the value of behavioral research. Since rats are small, clean, relatively inexpensive, easily handled and maintained, widely available, have short twenty-one day gestational periods, and a short two to three year lifespan, their use as research subjects offers many advantages. These advantages are amplified in application to research problems that require large numbers of animals [45]. The most important reason for why the author selects rats is the association with the numerous previous researches using rats in animal psychology. A great number of rats had been used in Skinner's experiments to study the learning

skills and psychological states of animals, resulting in significantly substantial research achievements [8], [27], [28].

Although non-human primates (e.g. monkeys ) offer several potential advantages over other species and some behavioral tests can be adapted to allow testing of both humans and non-human primates by the same paradigm [29-30], the small rats is better than large non-human primates when considering the development of robots and experimental apparatuses. Furthermore, it is expected that the findings or methods of experimental and analysis obtained from these prior researches using rats can be introduced in this research involved in robot-rat interaction. Therefore the rats are considered as the optimal animal subjects for this research.

### 1.3.2 Overview System

To achieve the objective, the author proposes to develop a novel robot system to interact with animals. It should model the interaction between the robot and rats. The sociality of rats such as stress level can be analyzed and controlled based on the modeled interaction. As more imitative behavior of rats guarantee the similarity to the interaction between real rats, the novel robot system should mimic more behaviors of rats. The robot is to replace the real rat in the animal experiments, if it can better imitate the shape of rats, more attention and higher preference can be drawn by the rats with better shape imitation. Furthermore, the robot should be furnished with good cognitive skills to recognize the behavior of rats, as well as to improve the automaticity. The overview system is illustrated in Figure 1.22.

# 1.4  Related Research

The relationships among partner, rat behaviors and stress have been studied and analyzed in previous researches. [14] Described that physical activity had been clearly validated as one of the main indices of depression, and animal work along these lines had been able to elucidate mechanisms by which this may occur. Therefore animal models hold an important role in helping us understand the complex interrelationship between mental health and physical activity. [40] Verified how the locomotor and exploratory behavior influenced rodent anxiety by conducting OFT. [42] Introduced that the amount of social activity exhibited by the partner (as influenced by its own social history) may be viewed as one more important environmental

factor that determines the test subject's social behavior. Thus, the level of social activity of the play partner (low socially active or high socially active) should be manipulated to provide information about the role of social environmental factors in modification of social activity in adolescence. In [50], experiments conducted between rats identified the extrinsic influences such as partner's playfulness on play fighting in rats. The results revealed that play appeared to be contagious, in that a high playing animal stimulated its partner to play frequently as well. In this research, the author proposes to use the rat-like robot to play as the role of partner in animal experiments is promisingly able to adjust the stress level of rats successfully. For example, the robot can play socially active with real rats to create friendly relationship with rats to decrease the stress level, which suggests that the social activity of rats exposed to friendly robot will possibly rise. The basic problem is how to develop a bio-inspired robot to be able to interact with animal naturally.

When regarding biologically inspired robots, many researchers have been fascinated by the possibility of interaction between a robot and its environment, and by the possibility of robots interacting with each other [51]. In the early 1990s, Deneubourg pioneered the first experiments on stigmergy in simulated and physical "ant-like robots". After that, numerous researches have been conducted on collective robots [52], [53], as well as using robots as models for studying social insect behavior [54]. As described in [55], a robot can be defined as a machine that is able to interact physically with its environment and perform some sequence of behaviors, either autonomously or by remote control. In recent years, there has been a transition from robots that, once set in motion, 'blindly' follow a particular programme, to ones that can interact with their environment, learn and even adapt [56–58]. This creates many opportunities for the use of robots in experimental biology, which is called "biorobotics" defined as the intersection of biology and robotics. The common ground is that robots and animals are both moving, behaving systems; both have sensors and actuators and require an autonomous control system that enables them to successfully carry out various tasks in a complex, dynamic world [59]. Recently, there are many robots in biological research [60–63] developed, however less focuses were on the interactive component, which is a recent technological development and has become an important component of studies on animal behaviors [64], [65].
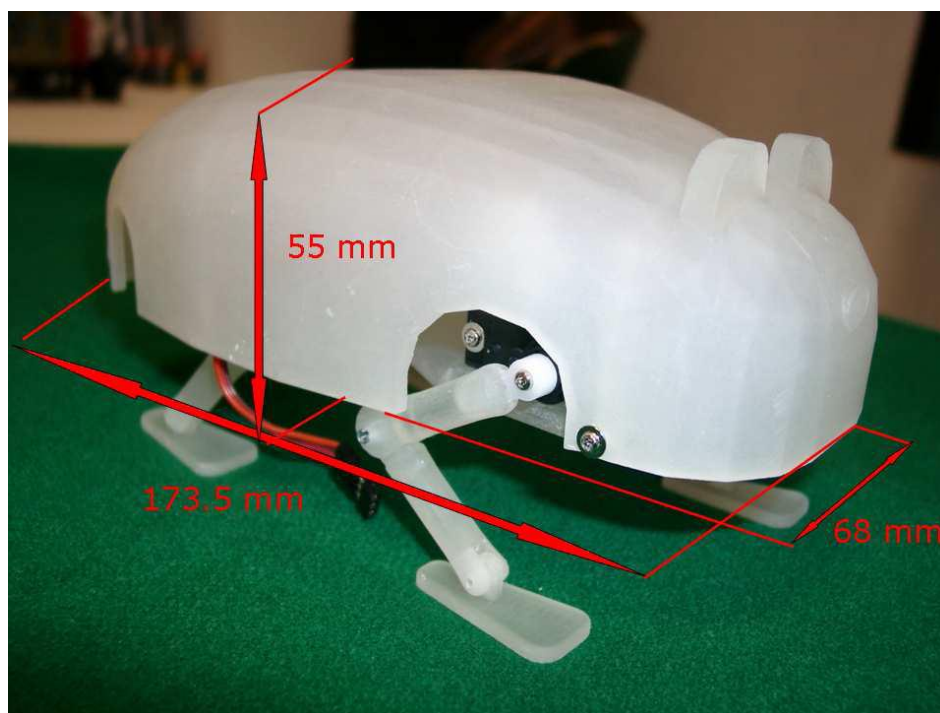
Figure 1.23 Rat-like robot named Raton Primero with hard cover: the size of this robot is approximately equal to mature rats
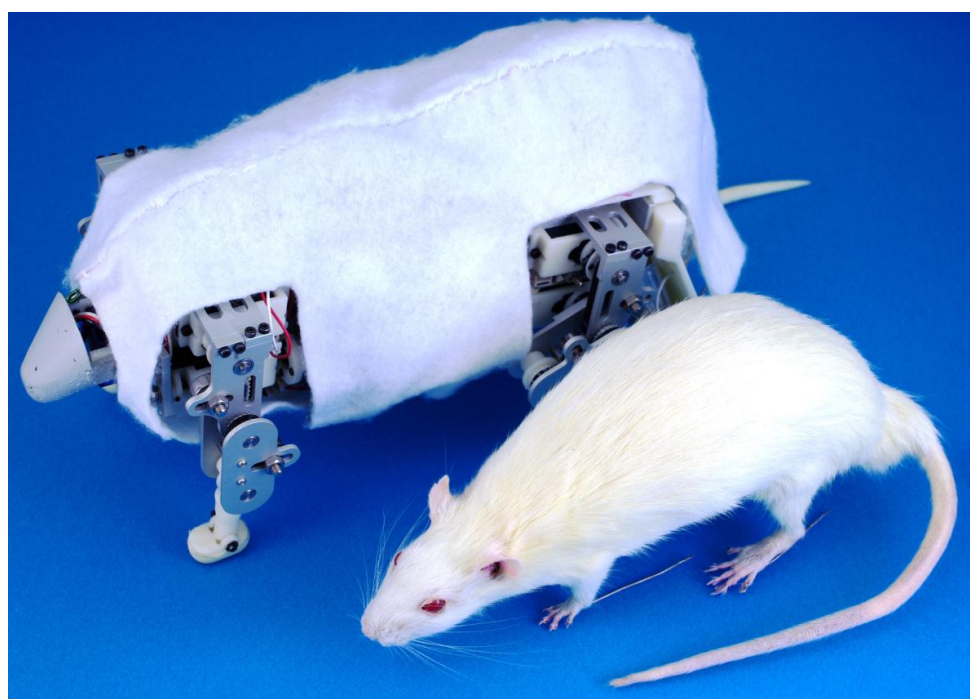


Figure 1.24 Rat-inspired robot WR-1 and stuffed mature rat

Interactive robots enable us to investigate entire interaction sequences where formerly scientists could only provide an animal with a single stimulus and then wait for a response [55]. However, animal interactions involve behavioral sequences that were previously difficult to test experimentally in a standardized way. Particularly relevant behavioral contexts that can involve lengthy interaction sequences include friendly, agonistic behaviors. This suggests that the design of an appropriate body and behaviors of the robot for animal experiments must originate from relevant sensory modalities and behaviors of the animal under study. However, unlike the InsBot and PoulBot robots, in our case the robot should look like the real rats to replace rat-rat interaction.

## 1.5 Structure of This Thesis

The reminder of the thesis is laid out as following (Figure 1.25):

**Chapter2 - Mathematical Model to Represent the Stress Level of Rats.** This chapter reveals that the complicated relationships among rat behavior, rat stress and robot behavior in robot-rat interaction system can be represented by specified mathematical models. Principal component analysis (PCA) is employed to specify the coefficients of proposed mathematical models. Likewise, linear discriminant analysis is used to confirm the effectiveness of the specified mathematical model.

**Chapter3 – Development of Rat-like Robots to Interact with Real Rats.** This chapter describes the design and development of several bio-inspired mobile robots. The purposes of these robots are to work as an experimental tool to study social interaction between rats and robots. The robot should be developed with a shape similar to a real rat the capability to mimic typical actions of a rat during robot-rat interaction. The final goal of robot development is to use the developed rat-like robot to analyze the behavior of mental disorder model rats in realistic psychological and pharmacological application for mental disorder treatment.

**Chapter4 – Image Processing and Behavior Planning for Robot-rat Interaction.** This chapter describes an automated video processing and behavior analysis system to replace the traditional manual annotation, and improve adaptivity of the robot to interact with rats. The robot behaviors are generated based on the rat behavior recognition to meet the purpose of experiments. In general, the robot will generate friendly or stressful behaviors respectively, to become the friend or opponent to the rat accordingly.
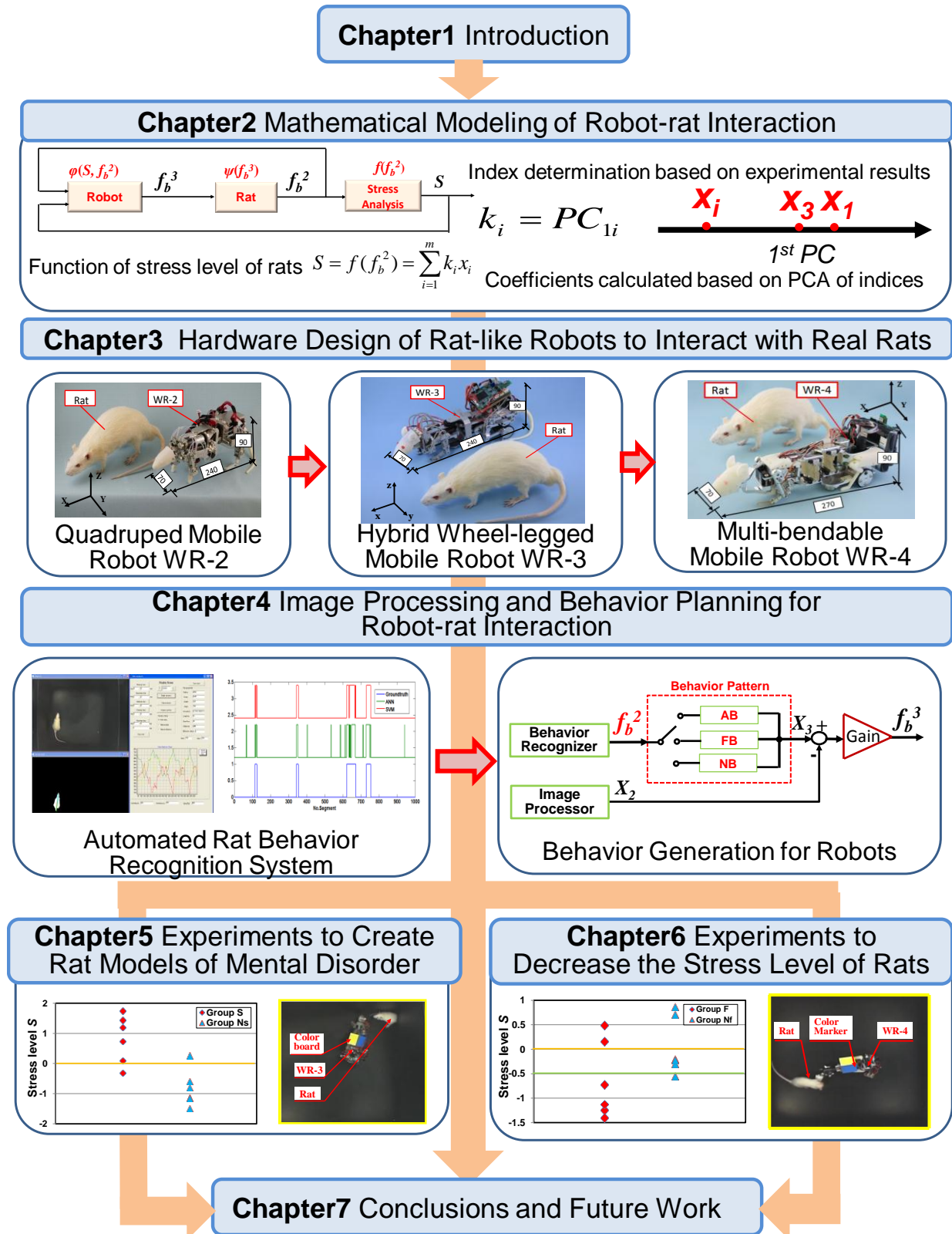
Figure 1.25 Outline of the thesis

**Chapter 5 – Development of Rat Models of Mental Disorder.** In this chapter, the focus of robot-rat interaction conducted is to put stress to rats, and make them become mental disorder by using the rat-inspired robot WR-3. We succeeded in the development of rat models of mental disorder, which exhibited low activities during mature period by exposing stress using the robot during immature period. Likewise, the experimental results are evaluated by the mathematical model described in Chapter 2.

**Chapter 6 – Novel Experiment Protocol to Reduce the Stress of Rats.** Several robot-rat interaction experiments introduced in this chapter are to create friendly relationship between rats and the robot WR-4. Likewise, we used the model specified in Chapter 5 to evaluate the interaction results between real rats. This kind of interaction is promisingly to be used for decreasing the stress level of rats.

**Chapter 7 – Conclusions and Future Works.** This chapter introduces the conclusions of the whole thesis and the further possible research theme from this thesis.

Chapter 2

# Mathematical Modeling of Robot-rat Interaction

## 2.1 Introduction

### 2.1.1 Background

Regarding our research, the social interaction between rats can be generally divided into three types: agonistic, friendly, neutral. The different kind of interaction may affect the psychology status of rat subjects. Agonistic interaction easily induces stress in rats, while friendly interaction makes them more active and therefore improves anti-anxiety ability. Neutral interaction is conducted mostly for comparison with other two types of interactions. Therefore the validity of the interaction can be evaluated by assessing the stress level. In conventional animal experiments, the stress level is assessed generally by scoring the motion parameters (frequency of rearing, grooming, amount of movement, etc.). Some experiments were conducted to seek the relationship between the behavior and stress in RMMD. [14] Introduced that decreased activity or immobility had been linked to learned helplessness paradigms and taken as evidence that this represents a viable animal model for depression in humans. Various lines of animal investigation have demonstrated that exercise favorably influences a number of biochemical factors involved in neurogenesis, neural plasticity and neuroprotection which are key elements in overall brain health. In [40], several ethologically relevant tests (OPT, SIT,

etc.) of anxiety-like behavior have been presented as a representative sampling of the broader collection of assays designed to assess anxiety-related behavior in mice in the field of behavioral neuroscience. Environmental factors have been shown to change social interaction. Rats exposed for 5 min to the odour of a cat or fresh rat blood showed significant anxiogenic effects when later tested in the SIT [66]. However, this thesis is focusing on the behavior shift due to the behaviors of the partner. Therefore, the researches such as [42] involved with partner preference in rat models are similar to this research. Additionally, the author considers that the subject showing high preference to its partner performs more play behaviors and results in more locomotor activity.

To improve the controllability and reproducibility, the author proposes to integrate robot technology into the animal experiments, which is called robot-rat interaction system. Besides, the advantages of the robot technology make it easier to measure and evaluate the robot-rat interaction quantitatively. Therefore, the complete relationship in the interaction can be modeled quantitatively.

### 2.1.2 Objective

As narrated in the preceding chapter, the author assumes that there are quantitative relationships between robot behavior, rat behavior and the stress level of rats.

1) In this chapter, the author attempts to clarify the general and quantitative relationships among rat behavior, the stress level of rats and robot behavior by using the robot-rat interaction system. In our current progress, the relationship between the rat behavior and its stress level can be derived based on previous research and experimental results.

2) The motion parameters can be used to estimate the stress level of rats. The author propose to use the linear combination of these motion parameters to calculate the stress level of rats. To specify this linear mathematical model, linear regression should be performed.

Therefore, a linear mathematical model has been derived to represent the rat behavior and its stress level. The methodology is introduced in detail in the following section.

## 2.2  Mathematical Model

### 2.2.1 Robot-rat Interaction System

To meet the research objectives, the author proposed a hypothetical-mathematical model to specify these complicated relationships in robot-rat interaction (Figure 2.1). Based on the relationship equations, the robot is able to control the rat behavior quantitatively, while the behavior of the robot is generated correspondingly to the recognized behavior and calculated stress level of rats.

Furthermore, detailed description of the system to specify the mathematical model can be seen in Figure 2.2. A CCD camera installed in the top grabs the motion images between the rats and robot. Based on image processing of the rat behavior $f_b^1$ video sequences, the motion parameters such as body length $l$, rotational angle $\theta$, locomotion speed $v$, etc., can be extracted. These parameters serve as the input vector $X_1$ of classifier (SVM or NN), and the behaviors of rats can be classified, i.e. recognized, after training appropriate number of input vector patterns. The motion pattern of robot $X_3$ depends on the recognized rat behavior $f_b^2$. Likewise, image processing serves to calculate the motion parameter $X_2$ comprised of motion parameters of robot $X_2^{robot}$ (e.g., $v$, $\theta$), rat $X_2^{rat}$ (e.g., $v$, $\theta$) and the motion relationship $X_2^{r-r}$ (e.g., the distance between robot and rat $d$). $X_2^{rat}$ varies individually, as well as with experimental conditions. Therefore, in this methodology, the robot is endowed with the capability of generating behavior $f_b^3$ adaptive to environmental conditions and individual differences in rats.

The robot-rat interaction experiments will be conducted as above-mentioned. For example, to create RMMD, the robot will continuously output agonistic behaviors (e.g., mounting, chasing, attacking) to give social stress to rats [33]. The repetitive experiments will last till the stress of rats accumulated approximately to the extent of mental disorder. The mathematical model contributes to generate robot behaviors based on the function $\varphi(S, f_b^2)$, as well as to analyze the stress level based on the function $f(f_b^2)$. Similarly, to keep friendly relationship with rats, the robot will continuously output friendly behaviors (e.g., following, rearing when the rat rears). Similar to the experiments conducted to create RMMD, $\varphi(S, f_b^2)$ generates required robot behavior, while $f(f_b^2)$ results in stress level of rats. Also in this case, $f(f_b^2)$ shows the degree of friendliness between the robot and rats. In both cases, $\psi(f_b^3)$ serves to derive $\varphi(S, f_b^2)$ when integrating with $f(f_b^2)$.

As mentioned in the objective, the stress level of the rat is determined by its behavior, so it can be calculated at first. In this thesis, the author will show the current process, that is the determination of the stress level of rats.
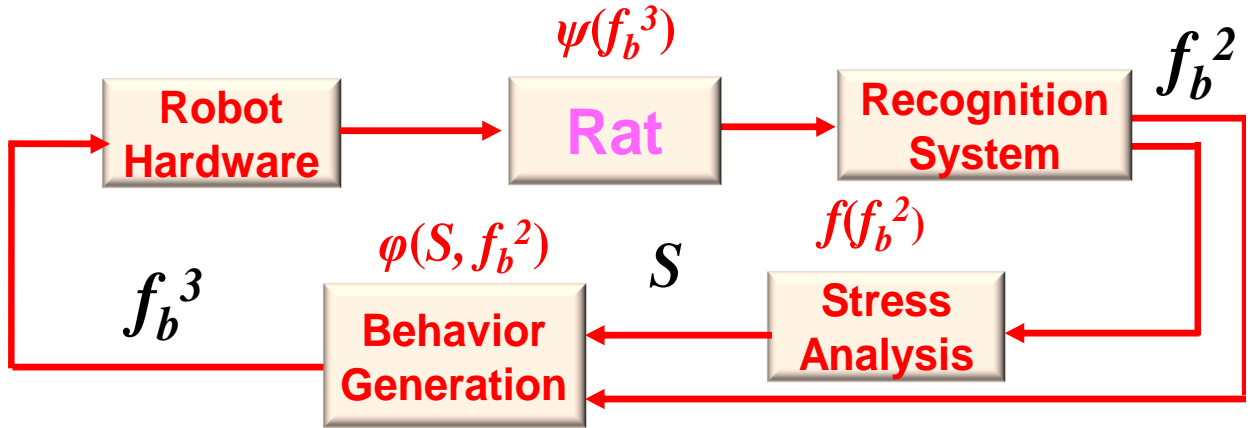


Figure 2.1　Mathematical modeling of the proposed novel robot-rat interaction system. Note that $f_b^3$ means generated robot behavior, $f_b^2$ rat behavior, $S$ stress level of rats; $\varphi(S, f_b^2)$, $\psi(f_b^3)$, $f(f_b^2)$ reveal the relationship from $S$ and $f_b^2$ to $f_b^3$, from $f_b^3$ to $f_b^2$, from $f_b^2$ to $S$ respectively
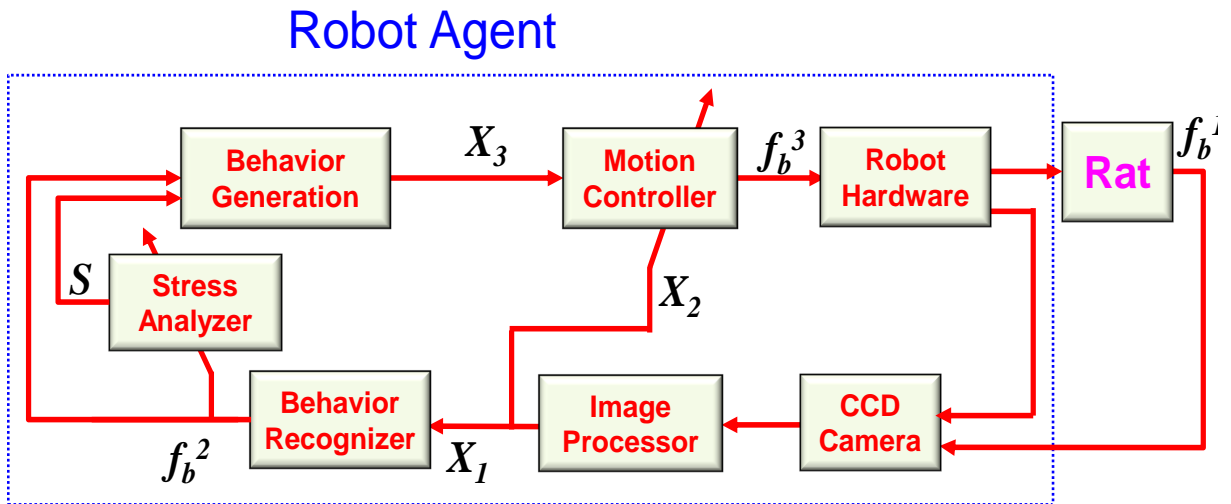


Figure 2.2　A robot-rat interaction system to specify the proposed mathematical models

### 2.2.2 Relationship between Rat Behavior and Stress Level of Rats

A person who has experienced much stress, such as violence or lack of affection, during childhood has a higher risk to suffer from mental disorders after growing up [69], [70]. On the other hand, the person who grows up in rich environment, surrounded many playful items and moderate stimulus, tends to be active and clever after growing up. Therefore, the author considers that the stress level of rats will be very high when attacked by a robot. On the contrary, the rats exposed to a friendly robot may be induced with low stress, and might be shaped with high anti-anxiety.

As is well known to all, the people with depression are not active as normal people. Furthermore, in [67], the activity of the rats was significantly decreased when exposed to the robot outputting stressful behaviors (refers to the behavior generation described in Chapter 4). This kind of interaction experiment can be called stress exposure [70] psychologically. The activity of rats are determined mainly by the amount of movement $a_m$, rearing frequency $f_r$, grooming frequency $f_g$ [29], etc. If the rats are attacked by the robot in stress exposure experiments, they should avoid moving toward and approaching the robot (refers to robot-rat distance $d_{rb-r}$, etc.). To summarize, $f(f_b^2)$ derived by the following equation is used to represent the stress level of rats.

$$S \ = f(f_b^2) = \sum_{i=1}^{m} k_i x_i \tag{2.1}$$

Note that $x_i$ ( $i = 1 \ldots m$) means variable such as $a_m$, $f_r$, $f_g$, $d_{rb-r}$, etc. $k_i$ is the coefficient of each variable $x_i$. The value of $k_i$ indicates how each variable $x_i$ contributes to the stress level of rats. When the value of $f(f_b^2)$ is low, the stress level of rats is high, and vice versa.

Based on the relaxation technique [71] used to release stress for people suffering with mental disorder, we consider that the stress level of rats might decrease when exposed to a robot that continuously act friendly behaviors (refers to the behavior generation described in Chapter 4). Obviously, the robot should be active when playing as the role of friendly partner in robot-rat interaction. Otherwise, it cannot even attract the attention of rats, not to mention drawing their interests. [5], [12] Showed that rats exposed to active partners became more social active. This suggests that the social activity of rats exposed to friendly robot will possibly

rise. Consequently, the degree of friendliness between the rats and robot can be partially expressed by the activity level (the amount of movement $a_m$, rearing frequency $f_r$, grooming frequency $f_g$, etc.). As described in [42], the rat's preference to the robot is a significantly important index to express the friendliness between the rats and robot. When a rat that shows high preference to the robot should move toward and approach the robot more frequently, which can be expressed as the frequency of approaching to the robot $f_{ar}$, etc. Therefore, Eq.2.1 can be used to evaluate the friendly relationship between the rats and robot as well.

An issue that should be firstly addressed involves the determination of $x_i$ and $k_i$. Regarding $x_i$, we determine it by analyzing the interaction experimental results from between the robot and rats. There are 2 groups (Group A and Group B) of experimental rats reared under the same housing conditions, and each group has the same number ($n$=6). In the RSIT for stress exposure, rats of Group A are exposed to the robot outputting stressful behaviors; while the rats of Group B are exposed to the robot outputting neutral behaviors (refers to the behavior generation described in Chapter 4). Each observed parameters $x_i$ in rats of 2 groups will be compared by Student's t-test. The parameters with significant differences (or approximately with significant differences) between Group A and B will be selected as the variables of the
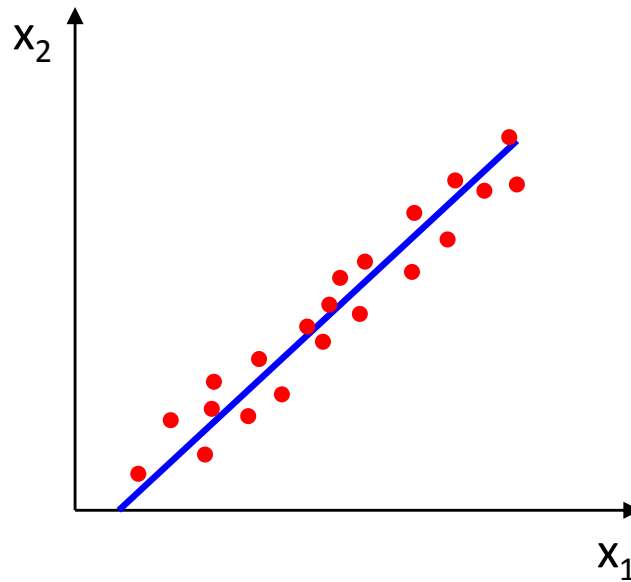


Figure 2.3 Linear least square fitting. $x_1$ and $x_2$ are the coordinates of sampled data (similarly hereinafter).

stress level of rats. In case of reducing stress (friendly interaction), the only difference is that, rats of Group A are exposed to the robot outputting friendly behaviors.

In general, the behavior of rats is determined by both intrinsic and extrinsic factors. The intrinsic influences involve housing conditions and inheritance, which can be controlled with human intervention. In this research, the rats used in the same experiment were born and reared strictly under the same conditions to decease the individual variability before test. Therefore, the behaviors of rats can be considered to be mainly determined by the extrinsic factors, that is the behaviors of the robot in this thesis.

### 2.2.3 Specification of Mathematical Model Coefficients based on PCA

The coefficient $k_i$ in Eq.2.1 represents how each variable contributes to $f(f_b{}^2)$. Determine these coefficients are equal to estimate the parameters of the function. There are several candidate methods listed below.

**Linear Least Square Fitting (LLSF)**: In statistics and mathematics, linear least squares is an approach to fitting a mathematical or statistical model to data in cases where the idealized value provided by the model for any data point is expressed linearly in terms of the unknown parameters of the model. The resulting fitted model can be used to summarize the data, to predict unobserved values from the same system, and to understand the mechanisms that may underlie the system (Figure 2.3). The LSF [72] technique is the simplest and most commonly applied form of linear regression and provides a solution to the problem of finding the best fitting straight line through a set of points. However, as the number of variables in Eq.2.1 should be at least two, so only linear least square fitting is not suitable to determine the coefficients. The feature reduction method can be used to decrease the number of variables though, to what degree each variable contributes to the stress level is not clear. In addition, the calculated results of LLSF are difficult to classify the rats under different interactions.

**Linear Classifiers (LC)**: In the field of machine learning, the goal of statistical classification is to use an object's characteristics to identify which class (or group) it belongs to. A linear classifier achieves this by making a classification decision based on the value of a linear combination of the characteristics. An object's characteristics are also known as feature values and are typically presented to the machine in a vector called a feature vector [73]. If the input

$$y = f(\vec{w} \cdot \vec{x}) = f(\sum_j w_j x_j) \tag{2.2}$$
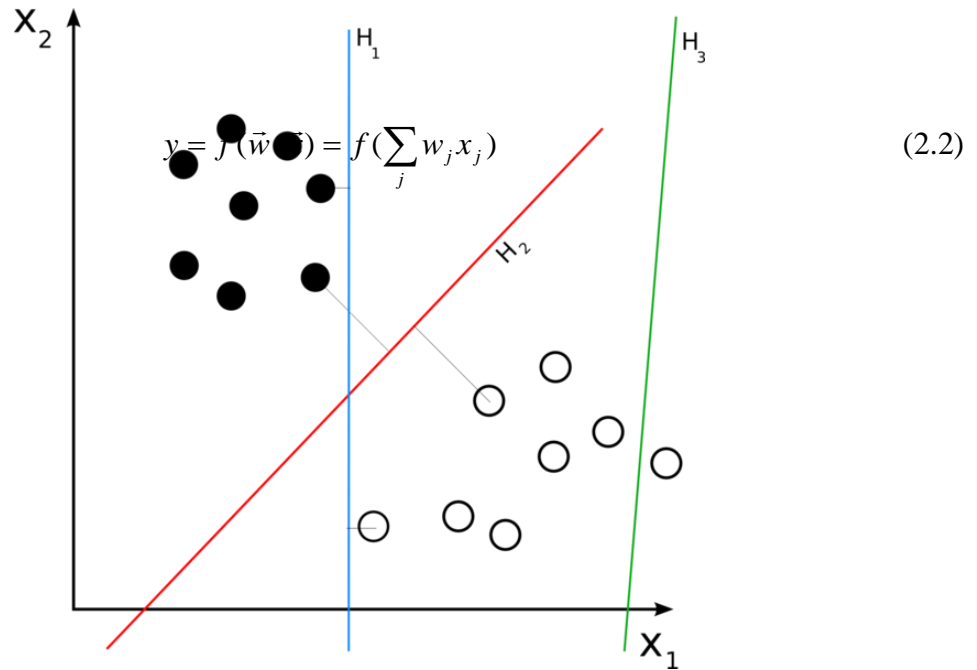
Figure 2.4 The solid and empty dots can be correctly classified by any number of linear classifiers. H1 (blue) classifies them correctly, as does H2 (red). H2 could be considered "better" in the sense that it is also furthest from both groups. H3 (green) fails to correctly classify the dots.

feature vector to the classifier is a real vector $\vec{x}$, then the output score can be derived as the following equation.

Where $\vec{w}$ is a real vector of weights and f is a function that converts the dot product of the two vectors into the desired output. The weight vector $\vec{w}$ is learned from a set of labeled training samples. Often f is a simple function that maps all values above a certain threshold to the first class and all other values to the second class. For a two-class classification problem, one can visualize the operation of a linear classifier as splitting a high-dimensional input space

with a hyperplane: all points on one side of the hyperplane are classified as "yes", while the others are classified as "no" (Figure 2.4). Linear discriminant analysis (LDA) [74] is a kind of algorithm to determine the parameters of a linear classifier $\vec{w}$. It attempts to express one

dependent variable as a linear combination of other features or measurements. However, the stress level results cannot be observed in advance, which means there are no responses in each vector.

**Factor analysis (FA):** FA is a statistical method used to describe variability among observed, correlated variables in terms of a potentially lower number of unobserved, uncorrelated variables called factors [75]. In other words, it is possible, for example, that variations in three or four observed variables mainly reflect the variations in fewer such unobserved variables. Factor analysis searches for such joint variations in response to unobserved latent variables. The observed variables are modeled as linear combinations of the potential factors, plus "error" terms. The information gained about the interdependencies between observed variables can be used later to reduce the set of variables in a dataset. Regarding the definition, suppose we have a set of $p$ observable random variables $x_1, \ldots, x_p$. The factor analysis model assumes that each variable consists of two parts: a common part and a unique part. Specifically, we assume that there are $m$ underlying variables or factors $\xi_1, \ldots, \xi_m$, so that

$$x_i - \mu_i = \sum_{k=1}^{m} \lambda_{ik} \xi_k + \varepsilon_i \qquad i=1,...,p \qquad (2.3)$$

Where $\mu$ is the mean of the vector $(x_1, \ldots, x_p)^T$. Without loss of generality, we shall take $\mu$ to be zero. The variable $\xi_k$ are sometimes termed the common factors since they contribute to all observed variables $x_i$, and $\varepsilon_i$ are the unique or specific factors, describing the residual variation specific to the variable $x_i$. The weights $\lambda_{ik}$ are the factor loadings. Eq.2.3 is usually written as

$$x = \Lambda \xi + \varepsilon \qquad (2.4)$$

$\Lambda$ is a $p \times m$ matrix, however, as $m < p$, it is not possible to invert this to express $\xi$ in terms of $x$ and hence calculate factor scores. So it is difficult to determine the combination coefficients in the matrix $\Lambda$. There are methods for estimating factor scores for a given measurement $x$. But this is yet one more difficulty which makes factor analysis less straightforward to use than PCA which will be introduced below.

**Principal component analysis (PCA):** PCA is a mathematical procedure that uses an orthogonal transformation to convert a set of observations of possibly correlated variables into a set of values of uncorrelated variables called principal components [76]. The number of principal components is less than or equal to the number of original variables. This transformation is defined in such a way that the first principal component has as high a variance as possible (that is, accounts for as much of the variability in the data as possible), and each succeeding component in turn has the highest variance possible under the constraint that it be orthogonal to (uncorrelated with) the preceding components. Principal components are guaranteed to be independent only if the data set is jointly normally distributed. Let $x_1, \ldots, x_p$ be our set of original variables and let $\xi_i$, $i=1, \ldots, p$, be linear combination of these variables, then principal components can be derived by the following equation.

$$\xi_i = \sum_{j=1}^{p} a_{ij} x_j \tag{2.5}$$

Eq.2.5 can be wrote as the following

$$\xi = A^T x \tag{2.6}$$

Where $\xi$ and $x$ are vectors of random variables and $A$ is the matrix of coefficients.

PCA is sensitive to the relative scaling of the original variables. So it is necessary to standardize the data so that the variables have equal range. A common form of standardisation is to transform the data to have zero mean and unit variance, so that we find the principal components from the correlation matrix. This gives equal importance to the original variables. Eq.2.6 relates the principal components $\xi$ to the observed random vector $x$. In general, $\xi$ will not have zero mean. In order for the principal components to have zero mean, they should be defined as

$$\xi = A^T (x - \mu) \tag{2.7}$$

for mean $\mu$. In practice is the sample mean $\mu$.

For the selection of components, probably the most common approach is the percentage of variance method, retaining eigenvalues that account for approximately 90% of the variance. The firstly few principal components are the most important ones, but it may be very difficult to ascribe meaning to the components. One way this may be done is to consider the eigenvector corresponding to a particular component and select those variables for which the coefficients in the eigenvector are relatively large in magnitude.

In summary, PCA is chosen to determine the coefficients of Eq.2.1 since it is able to reveal the internal structure of the data in a way which best explains the variance in the data,. As the variables selected in the rats of Group A and Group B have significant differences, they can be discriminated clearly when represented by the computed principal components. The author performs PCA to find the principal component coefficients $pc$ ($j = 1\ldots n$, $n$ is the number of used principal components) for each variable. In general, the first principal component coefficient $pc_1$ mostly indicates the variance of the data. Consequently the $k_i$ of is equal to $pc_{1i}$ (the first principal component coefficient of corresponding $x_i$) as shown in the following equation.

$$k_i = pc_{1i} \tag{2.8}$$

To confirm the correctness of the derived equation, the results from PCA are classified by the LDA. If the classified results are near to the results calculated based on the equation, the equation is proved to be effective.

# 2.3 Discussion

### 2.3.1 Modeling of Rat Behavior and Stress level of Rats

In the robot-rat interaction, the robot behavior, rat behavior and rat psychological status constitute the main elements for study. As the stress level of rats is significantly close to the mental disorder, which is one of the potential applications, the author is focusing on the stress lev-

el of rats at current progress. Although the stress level of rats can be estimated by many factors though, one of the main indices is the behavior parameters. The problem is that the relationship between rat behavior and stress level of rats is not explicit, so it is significantly difficult to specifically represent it. According to numerous previous research results, the stress level of rats can be represented by motion variables such as the amount of movement $a_m$, the frequency of rearing $f_r$, body grooming behaviors $f_g$, the distance between rat subject and partner $d_{rb-r}$, etc. Only the motion parameters come to brief estimation of the stress level of rats. Therefore, in the future, the physiological characteristics such as blood pressure, blood sugar, etc., should be considered as well. Likewise, it is necessary to collaborate with anatomy researchers to obtain the physical information of rats.

### 2.3.2 Modeling Method

It is possible to represent the complicated relationships between behavior and stress level of rats quantitatively by using mathematical model. Specifically, the author proposed to represent the stress level of rats by the linear combination of motion variables ($a_m$, $f_r$, $f_g$, $d_{rb-r}$). To confirm the coefficients of each variable, linear regression methods is needed. Comparing with other methods, PCA is more effective and straightforward to confirm how each variable contributes to the stress level. The reason is that PCA can be used as an unsupervised classification. It also provides the contribution ratio of each variable, which is as the coefficients of variable in the linear mathematical model. In addition, LDA will be used to evaluate the effectiveness of the classification based PCA.

# 2.4　Summary of this Chapter

In this chapter, after introducing the overview system, the author considered that the robot-rat interaction between the robot and the rat could be specified by a mathematical model. For the current progress, the stress level of rats and rat behavior can be determined quantitatively base the derived mathematical model.

1) The relationship between the behavior and the stress level of rats can be expressed by a linear function. The amount of movement, frequency of typical behaviors and preference are particularly important indices to the stress level of rats. The main problem

goes to how to determine the coefficients, that means to what degree each index contributes to the stress level of rats.

2) According to the analysis and comparison, PCA is proved to be effective and straightforward to determine the coefficients of this linear function.

# Chapter 3

# Hardware Design of Rat-like Robots to Interact with Real Rats

## 3.1 Introduction

### 3.1.1 Background

As mentioned in Chapter 1, to better control the experimental conditions and improve the reproducibility, we propose to use robot to conduct interaction experiments with real rats [31]. In this system, only the robot is considered as the experimental factors (refer to events and stimuli that change behavior) in this system. The robot serves to not only interact with rats but also control the stress of rats.

In the past decades significant progress has been made in the research on bio-inspired robots [77–80]. However, few animal-like robots had the capability to interact with animals [81–83]. In particular [82] presented general ideas on design and implementation of mini robots to study, model, and control mixed societies of animals and robots. In our previous research, several mobile robots have been developed to study the behavior of rats [42–45]. [37] Described an earlier version of the robot, called WM-6 as shown in Figure 1.19. Although this robot was in principle able to run as fast as rat ($v_{maxWM-6}$= 1 m/s), it was mainly used to perform the social action mounting. Furthermore it was not designed to accurately imitate the appearance of a real rat. As an improvement, in [84], a rat-inspired legged rat robot called Ra-

ton Primero (Figure 1.23) was developed to clarify the basic characteristics of a relationship between a rat and the robot. Although Raton Primero was able to walk, trot and stand, in order to perform similar postures and movements as real rats, it was incapable of doing social behaviors, such as rearing, sniffing, mounting and grooming. In [85] a robot called WR-1 (Figure 1.24) (Waseda Rat No. 1) that was in its appearance similar to a mature rat has been proposed. Although WR-1 was capable of expressing social actions such as rearing and grooming, it was significantly larger than a real rat and could only move at a low speed ($v_{maxWR-1}$ = 0.02 m/s) during walking or rotating.

### 3.1.2 Objective

Regarding the hardware design of the robot, as a requirement to do successful experiments, the shape and movement capabilities of the robot should be similar to a real rat. More imitative behaviors of the rat allow better similarity to the rat-rat interaction. Furthermore, better shape imitation can draw more attention and higher preference of the rats. As a short-term objective, we aim to design a rat-inspired mobile robot that has a shape similar to a real rat and also has the capability to mimic typical actions of a rat during social interaction. The final goal of this research is to use the developed rat-like robot to analyze the behavior of mental disorder model rats in realistic psychological and pharmacological application for mental disorder treatment. Below is the detailed description of the concepts and methods of the hardware design of three rat-like robots.

## 3.2  Hardware Design Methods

In the case of conventional interaction, two real, living rats are used to perform the experiments. According to the novel methodology, a rat-like robot is to replace one of the living rats in the interaction experiments. For this reason, we tried to produce a robot as exact as possible imitation of the shape and motion performance of a real rat. To naturally interact with a living rat, the dimensions of the robot should be similar to that of an adult rat. Besides, it should be capable of exhibiting mobility similarly to a real rat during social interactions, such as chasing, rearing, grooming and mounting, etc. Therefore the shape design of the robot is mainly determined by the characteristics and skeleton structures of the mature rat. From the observation

of rats and the reference to biological literatures [86], [87], the biological data of rats is available as shown in Table 3.1. The body dimension and weight of the robot are to be designed close to these parameters.

Table 3.1 the body dimension and weight of mature rats.

| Part | Parameter |
| --- | --- |
| Width | 50-120 mm |
| Height | 70-150 mm |
| Length | 200-350 mm |
| Weight | 300-800 g |

The x-ray figure of a mature rat as shown Figure 3.1, and it illustrates the proportions of the upper and lower foreleg, the upper and lower rear leg as well as the rat's neck and spine. Compared to other quadruped animals such as dogs or horses, the proportional length of a rat's spine to its forelegs and rear legs is larger. As shown in the figure, the length of the lower rear leg is a little longer than that of the lower foreleg, while the length of the upper foreleg and the upper rear leg are almost the same. Besides, the shape of the robot involves the motion performance. Actually, detailed behavioral analysis of the rats serves to determine the
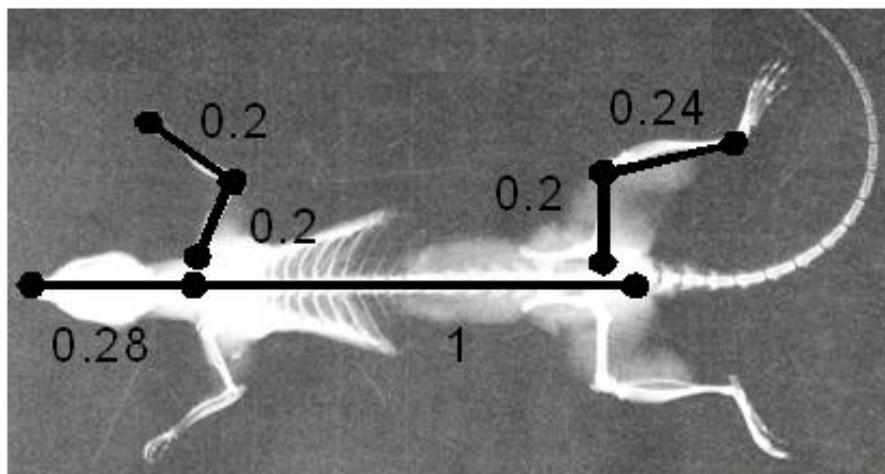


Figure 3.1 . X-ray picture of a rat and its body proportion. Given the length of the spine, that is 1 here, the length of other parts can be derived as cited above.

Figure 3.2 Behavior observation of the living rats
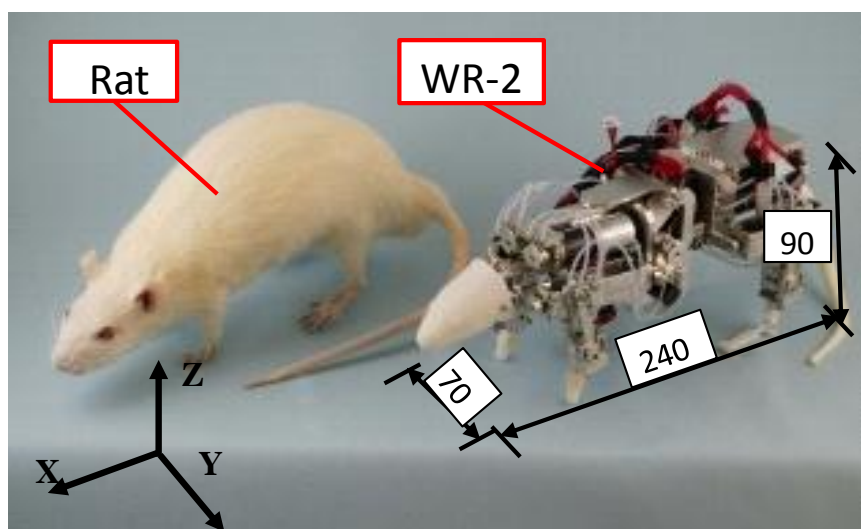


Figure 3.3 WR-2: a good miniaturization and imitation of rat shape. (Number unit: mm)

DOF configuration of the rat-like robot (Figure 3.2).

# 3.3 Quadruped Mobile Robot: WR-2

### 3.3.1 Design Requirements

Aiming at the interaction with real rats, a quadruped rat-like robot called WR-1 was previously developed [85]. As an improvement, a novel quadruped animal-like robot called WR-2

t=0.7 [s]          t=0 [s]

(a)                (b)
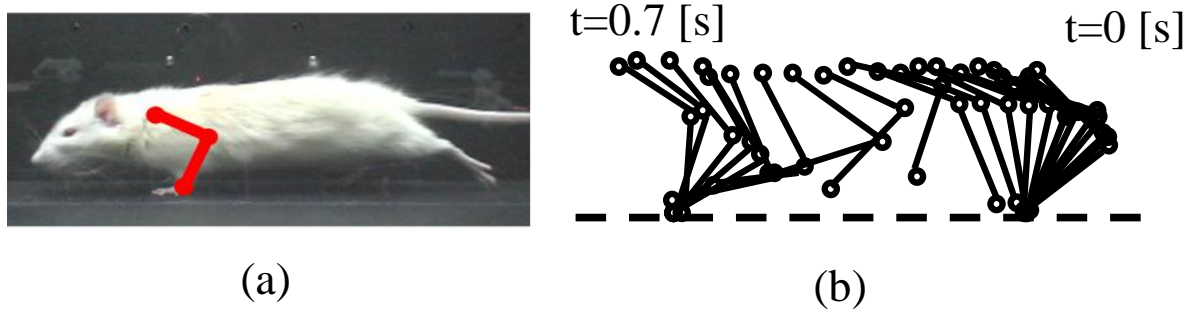
Figure 3.4 Capture of the rat walking gait in x-z plane. (a) The rat is walking through a resin cover plane at a speed of $V_{rat}$=0.45m/s. It is recorded by a video camera. (b) Analysis of the rat walking gait captured 30 ms once.

(Waseda Rat No. 2) (Figure 3.3) had been designed [88]. The quadruped animal-like robot WR-1 designed previously is similar to the rat's appearance and capable of expressing social behaviors such as rearing and grooming. Nevertheless it occupies much more space than an actual rat and could only move at a low speed ($V_{maxWR-1}$=0.02 m/s) during walking or rotation.

To meet with the requirements of the interaction with rats, as well as the suggestions from animal researchers, the robot used to interact with a rat should be designed similarly as a mature rat not only in the shape but also in the motion. Therefore, the author put emphasis on the body miniaturization and the motion performance improvement to develop WR-2 robot.

### 3.3.2 Modeling and DOF Configuration

The DOF arrangement of the robot is experimentally obtained from the motion analysis of mature rats. Walking motion of a rat is recorded by a video camera, and a stick diagram is obtained by visual analysis as shown in Figure 3.4. We analyzed the motion of both the arms and legs in not only x-z plane but also y-z plane. From the result of this analysis, we consider that each limb can be represented as a 2-DOF manipulator, a roll and pitch at the shoulder/hip, a pitch at the elbow/knee. In addition, rats have a flexible spine, and they can bend their body when they rear or groom by limbs. We consider these motions can be represented by a 2-DOF waist joint, a pitch and a yaw. Via this kind of motion and kinematical analysis, we consider that the muscle skeleton structure of the mature rat can be represented by the kinematic model as depicted in Figure 3.5.
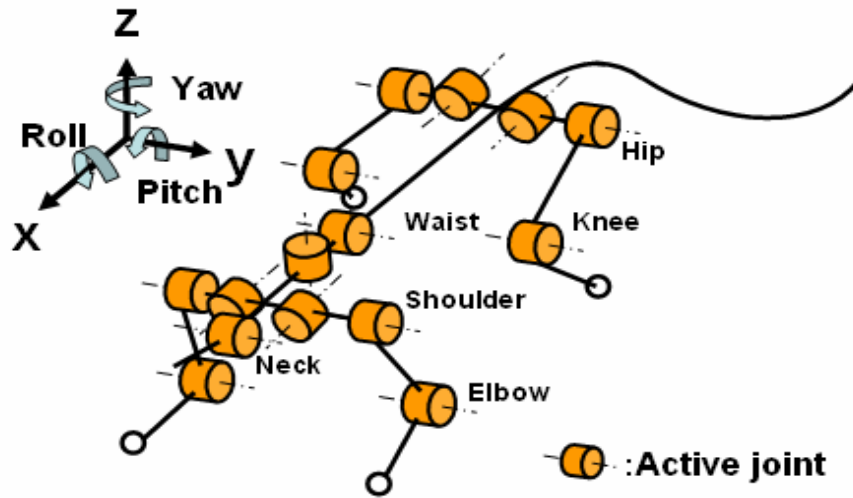
Figure 3.5 From the behavioral model and walking gait of an adult rat, the DOF arrangement of WR-2 is determined



(a)　　　　　　　　　　　　　　　(b)
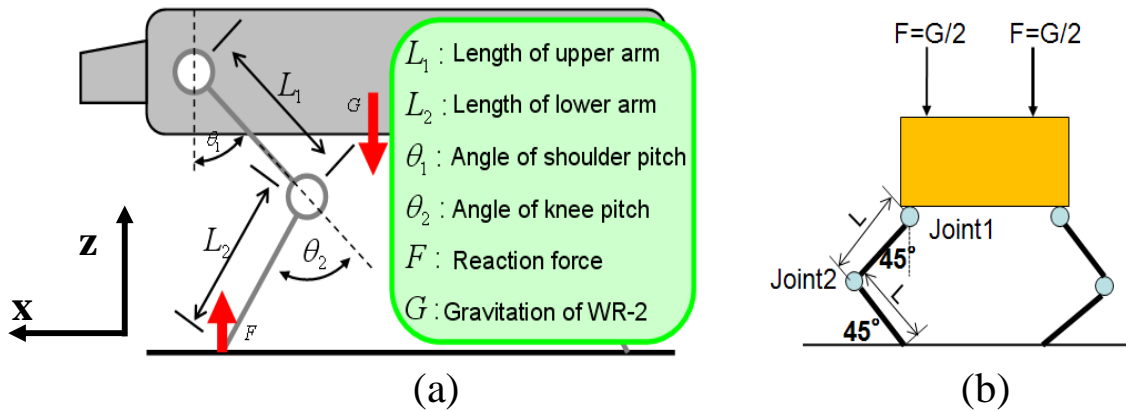
Figure 3.6 (a) Kinematics analysis of the limb of WR-2 was done to obtain selection criteria of the actuator, which is the output torque value of the DC motor here. (b) Calculate the maximum torque of joint

### 3.3.3 Mechanical Design

*A. Actuator Determination*

DC motors with rotary encoders are used in the limb with the consideration of miniaturization and feedback control. The output torque of each motor depends on the required force and

torque in each DOF of WR-2. Therefore, force and torque of every joint should be roughly calculated beforehand based on the kinematics analysis as shown in Figure 3.6.

When the quadruped robot is walking, most force on the limb is from the gravitation of the robot. The maximum force on one limb is $F = G/2$ when the body is supported by two limbs. As shown in Figure 3.6 (b), if the angle of femur and tibia with the ground is +45 respectively, the torque on joint1 is considered to be $T_1 = 0$. The joint2 should output torque $T_2 = F \cdot L \cdot cos\ 45°$ to support the robot. Here, as $F = G/2$, $L = L_1 = L_2$, therefore we can work out the required torque of this joint to determine corresponding DC motor specification. Given the symmetry, all the limbs act in the same way and we can select the same type DC motor for all the limbs. As the rearing and rotating behaviors are mainly achieved by the waist and neck, the axis of the waist and neck is actuated by a servo motor separately to simplify the control.

### B. Design of Limb

As shown in Figure 3.5, each limb is represented with 3 DOF, two of which are configured in the shoulder (and respectively, the hip) as the straight form of roll and pitch and the other one is configured in the elbow (and respectively, the knee) as pitch. With the same amount of DOF in the roll direction, the center of gravity can be moved simultaneously during dynamic walking. From the arm structure described in Figure 3.7, motor DC1 and DC2 are used for pitch motion, while motor DC3 is set for the roll movement. In correspondence with the roll of the limb, the end of each limb is designed in the shape of a hemisphere.

The shoulder pitch and the elbow pitch are driven by the DC motors via the wire and outer-tube connection mechanisms as depicted in Figure 3.8. The DC motors used to drive these joints are installed in the body. However, this kind of wire and outer-tube mechanisms may yield buckling of the tube and friction between the wire and the tube. Consequently, fluorine resin is used as the outer-tube material to alleviate these demerits to some extent.

### C. Design of Waist and Neck

The behaviors such as rearing and grooming are required in social interaction test. These motions are feasible when two DOF are configured as the yaw and the pitch in waist and one DOF is arranged as pitch in the neck.
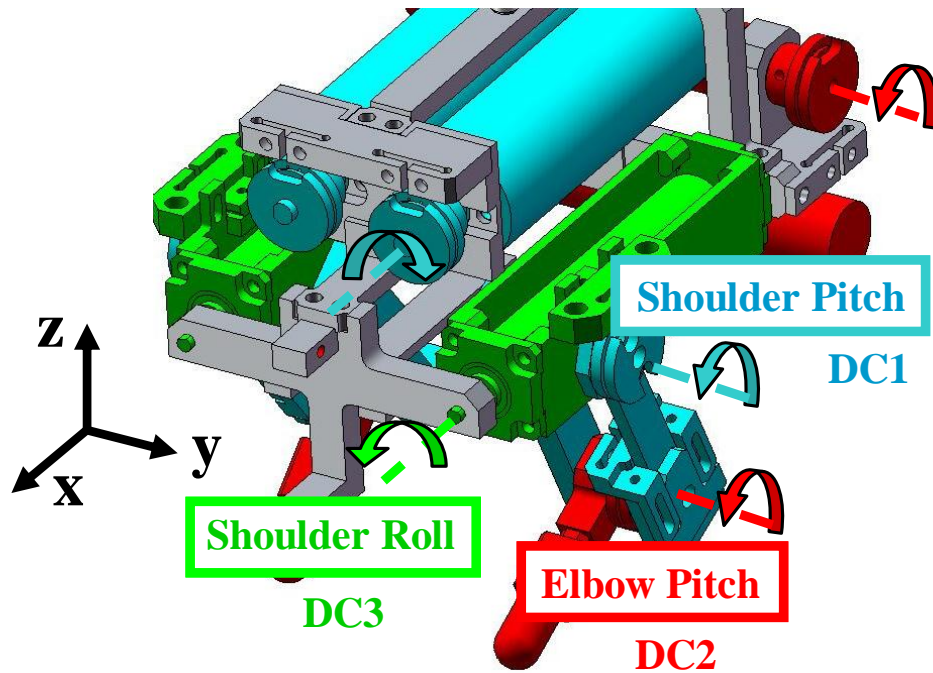
Figure 3.7 The mechanical design of the left arm. It consists of 3 DOFs: roll and pitch of the shoulder joint and pitch of the elbow joint. The three DC motors are assembled in the body via wire and outer-tube driving mechanism to actuate corresponding joints.
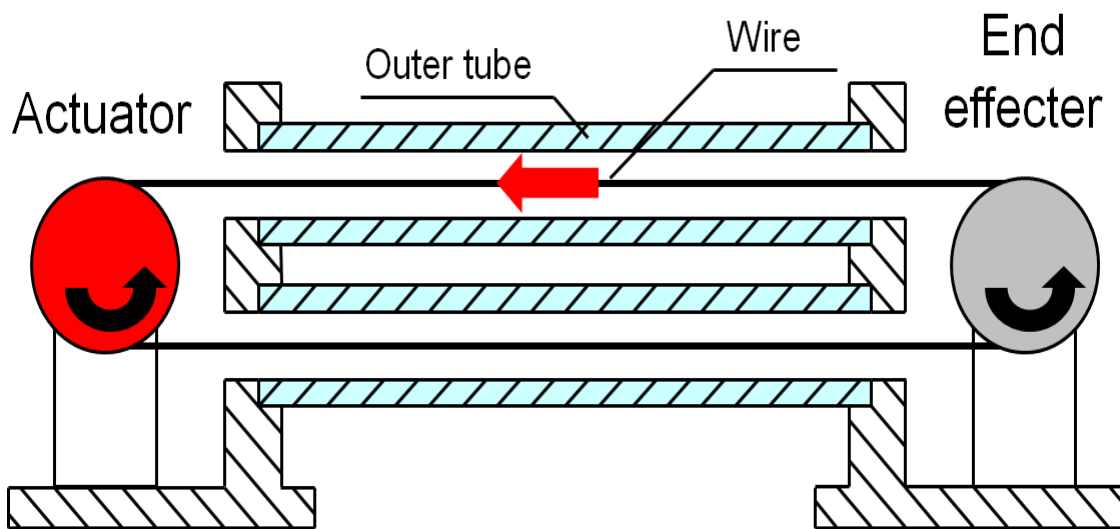


Figure 3.8 Wire and outer-tube driving mechanism: the wire is fixed at the actuator and the output object. The length of the tube is constant. As the tube is flexible, the actuator can be placed without many constraints.
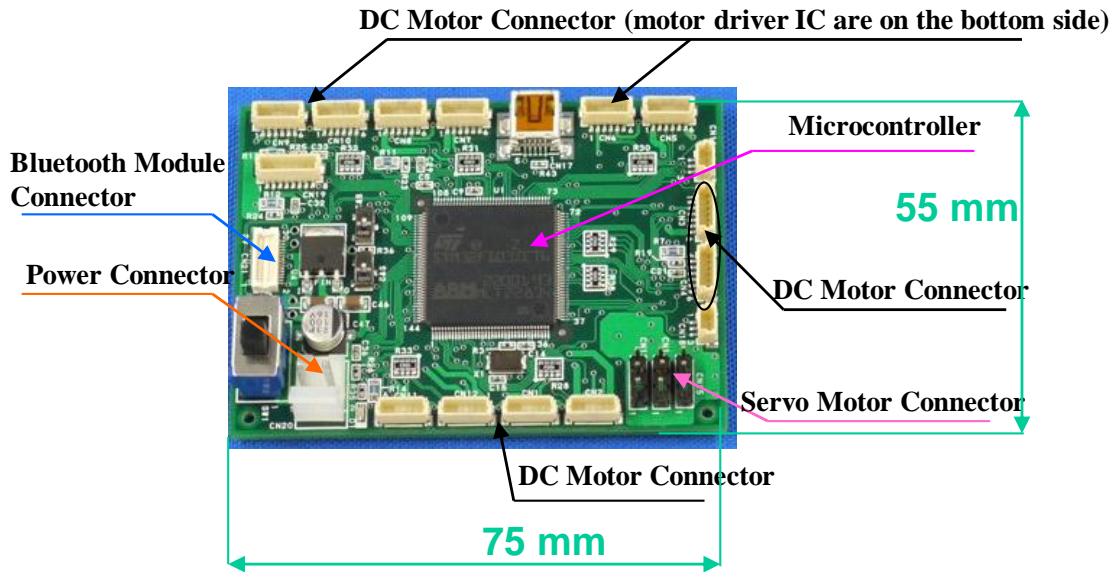
Figure 3.9 Control circuit of WR-2, a microcontroller that is STM32F103ZE6T and motor drivers (each drives 2 DC motors) are embedded in this circuit board
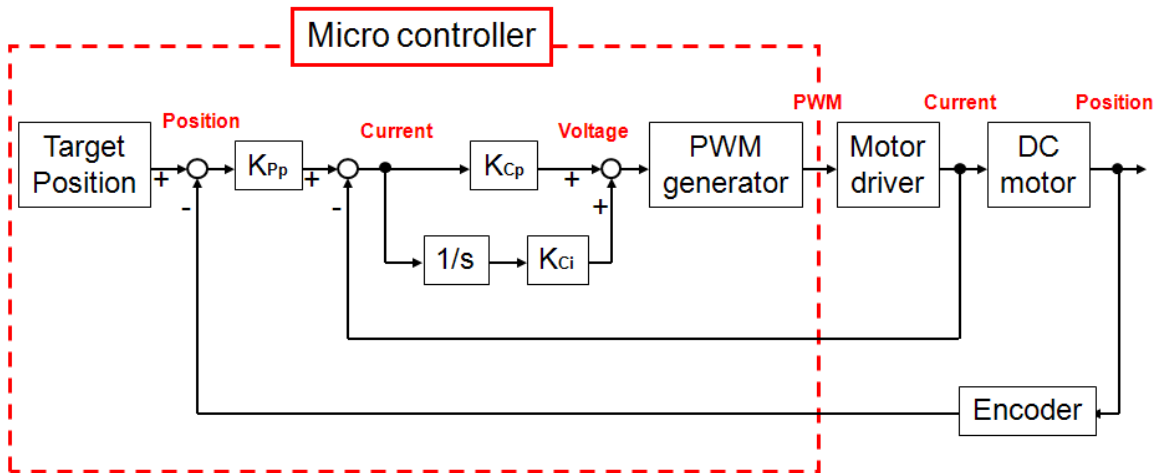


Figure 3.10 Control flow chart, position feedback control and current feedback control has been used to accurately control DC motors. Note: $K_{Pp}$ : position proportional gain, $K_{Cp}$ : current proportional gain, $K_{Ci}$: current integral gain

## 3.3.4 Control System Design

A micro-control module and wireless data transmission module are embedded in WR-2. The robot is controlled by a PC via wireless communication with a microcontroller.

## A. Control of Motors

A dedicated electronic circuit used to control the DC motors of WR-2 was designed. As shown in Figure 3.9, a novel motor driver circuit board with the ability to control twelve DC motors and three servo motors synchronously has been developed. The main board is controlled by a microcontroller STM32F103ZE6T manufactured by ST Microelectronics. As previously narrated, the WR-2 motion mainly includes walking, rearing, grooming and mounting. These motion patterns are generated by an off-line pattern generator in advance. The motion pattern data is preloaded in the form of packages in the microcontroller as time-line data of each joint angle. The microcontroller controls the angle of each joint based on that pattern, when it receives the instructions from the PC.

Angle of each DC motor is controlled with the position servo control as demonstrated in Figure 3.10, which includes position and current feedback control. The microcontroller measures the angle of each motor from the encoder input data, and sends corresponding instructions to the motor drivers (direction and duty ratio of PWM) with a rate of 1ms. Signals (pulses) from the rotary encoders are counted using the external input interrupt functions. PWM pulses are generated using the hardware timer modules of the microcontroller.

## B. Walking Algorithm

In this project, we used moment compensation trajectory generation algorithm based on the ZMP (Zero Moment Point) stability criterion [89] to figure out robot dynamic walking pattern. According to this algorithm, the moment brought by any movements of the limb is compensated by the trunk to make the ZMP inside the support polygon at all time. This algorithm is composed by the following three main parts.

(1)　Modeling of the robot

(2)　Derivation of the ZMP equation

(3) Solving the exact solution of the ZMP equation that meet moment compensation trajectory with iterative calculation using the robot model

The quadruped walking robot has been modeled as shown in Figure 3.11[90]. In this walking system, the coefficient of friction for rotation around X, Y and Z-axis is zero at the contact point. According to this model and the ZMP stability criterion formula, the moment of a random point $p$ based on the absolute coordinate system O-XYZ can be derived as the following.

$mi$ : mass or particle i
$ri$ : position vector of particle i
$rp$ : position vector of P
O-XYZ : absolute coordinate system
$\overline{O}$-$\overline{X}$$\overline{Y}$$\overline{Z}$ : moving coordinate system

Figure 3.11 Kinematical model of WR-2

$$\sum_{i}^{AllParticles} m_i (r_i - r_P) \times (\ddot{r}_i - G) - \sum_{k}^{AllPo\,ints} \left[ (r_{Fk} - r_P) \times F_k + M_k \right] + T = 0 \qquad (3.1)$$
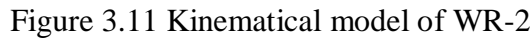
Where $T$ denotes the total torque act on the point $p$, $r_{Fk}$ the position vector of the actuation point by the $k$th external force or external moment. $F_k$, $M_k$ the $k$th external force and external moment which act on the point $k$ respectively.

From Eq.3.1, when the point p is considered to be ZMP, we can set $T = 0$. Thus, the following ZMP formula is obtained. Note that $r_{ZMP}$ denotes the position vector of the ZMP.

$$\sum_{i}^{AllParticles} m_i (r_i - r_{ZMP}) \times (\ddot{r}_i - G) - \sum_{k}^{AllPo\,ints} \left[ (r_{Fk} - r_{ZMP}) \times F_k + M_k \right] = 0 \qquad (3.2)$$

Furthermore, if the relative motion is taken into account and the external forces are ignored, the ZMP formula based on the moving coordinate system $\overline{O} - \overline{XYZ}$ linked with the particle $i$ can be derived by the following equation.

$$\sum_{i}^{AllParticles} m_i(\bar{r}_i - \bar{r}_{ZMP}) \times [(\ddot{\bar{r}}_i + \ddot{\overline{Q}} - \overline{G} + \dot{\overline{\omega}} \times \bar{r}_i + 2\overline{\omega} \times \dot{\bar{r}}_i +$$

$$\overline{\omega} \times (\overline{\omega} \times \bar{r}_i)] - \sum_{k}^{AllPoints} [(r_{Fk} - r_{ZMP}) \times F_k + M_k] = 0$$

(3.3)

Note that Q represents the position vector of the origin of $\overline{O} - \overline{XYZ}$, while $\omega$ the angular velocity vector of the origin of $\overline{O} - \overline{XYZ}$, $G$ the gravitation acceleration vector. Therefore, the determined foot trajectory and torso trajectory should satisfy this ZMP formula.

### C. Walking Pattern Generation

Quadruped walking pattern generator was developed based on the walking algorithm described in the preceding section. As shown in Figure 3.12, joints trajectory of the quadruped robot is generated in the following sequences.

1) According to the robot initial gesture, preset foot trajectory and ZMP trajectory.
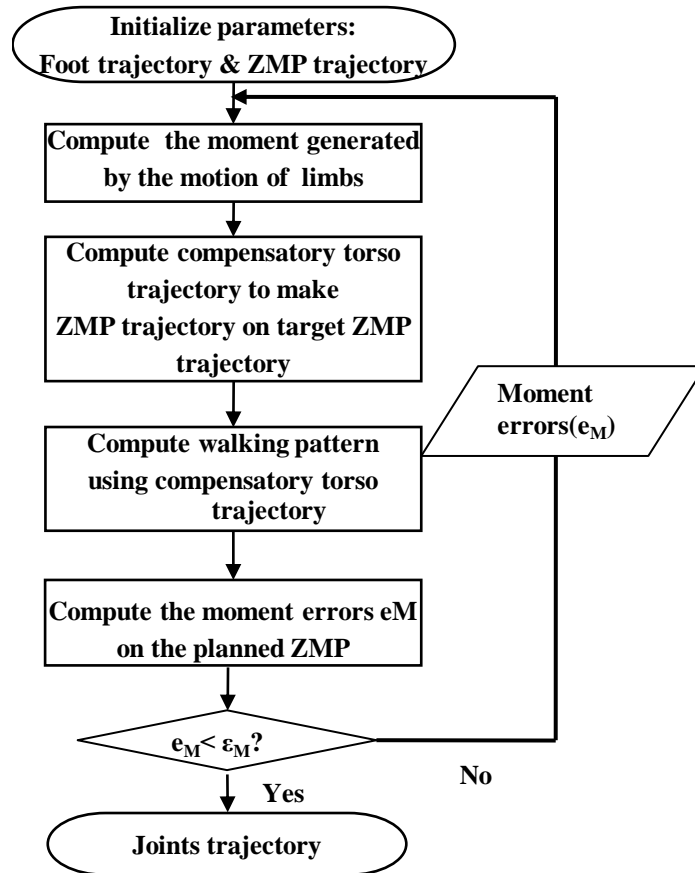


Figure 3.12 Iterative algorithm for generating quadruped walking pattern
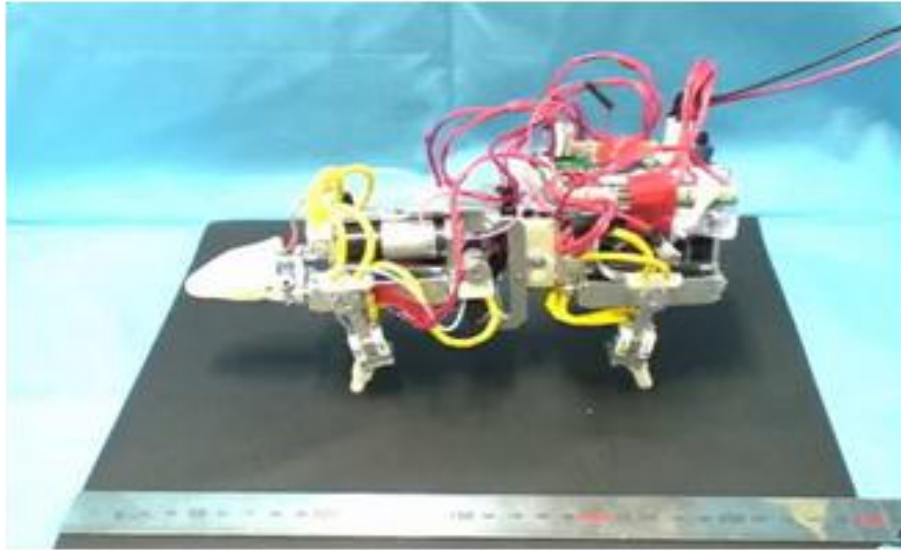
(a) Walking test of WR-2
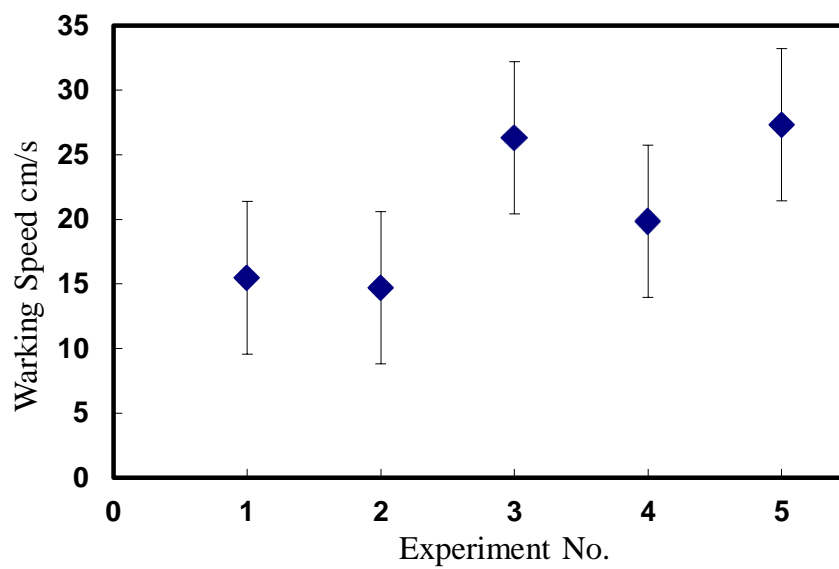


(b) WR-2 walking speed

Figure 3.13 Walking speed test and results of WR-2

2) Based on the preset foot trajectory and ZMP trajectory, the moment of motion limbs can be computed.

3) Torso moment compensation trajectory is calculated based on the linear model using the

compensation algorithm described previously.
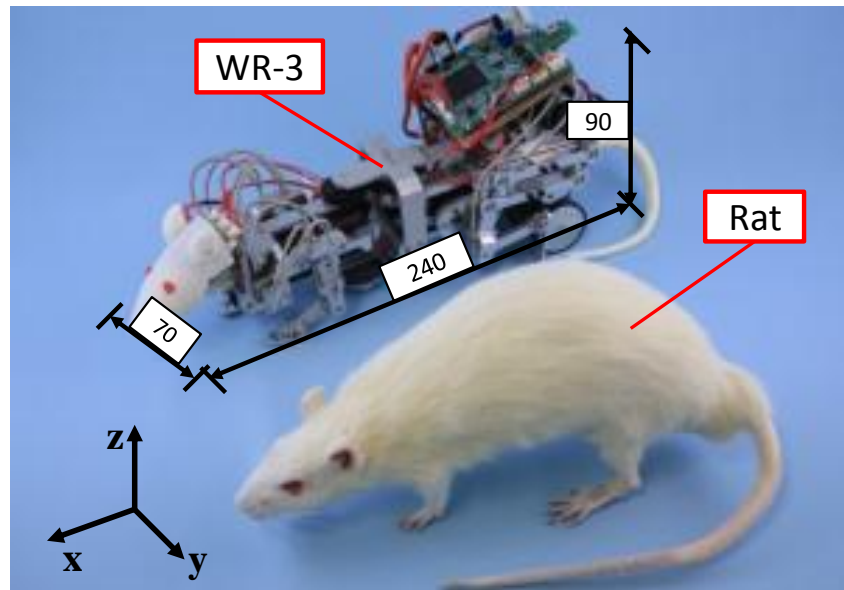
Figure 3.14 Shape of WR-3 and a mature stuffed rat. (Number unit: mm)

4) Then use the compensatory torso trajectory calculated in step (3) to generate walking pattern.

5) Compute the moment errors eM of planned ZMP trajectory, repeat the steps from (2) to (4) till the moment errors is less than the prescribed error (eM < εM).

6) Walking pattern generation and data output: all joint angles that are computed by using inverse kinematics based on the foot and torso trajectory are output as time-line data.

### 3.3.5 Performance Evaluation Results

As the performance evaluation experiment, walking speed test of WR-2 has been conducted. The experiment condition is illustrated in Figure 3.13(a), during each test, measure the distance and elapsed time, and the walking speed can be calculated. Five tests has been implemented as shown in Figure 3.13(b). From the results, the walking speed of WR-2 is between 15 mm/s and 30 mm/s. Comparatively, the speed of WR-2 is faster than that of WR-1, of which the speed is no more than 15 mm/s. However, from the standard deviation of five test values, the robot speed is not so stable.

# 3.4 Hybrid Wheel-legged Mobile Robot: WR-3

### 3.4.1 Design Requirements

In the preceding section, the quadruped walking robot WR-2 (Waseda Rat No. 2) capable of reproducing variety social behaviors of rats was introduced. This robot moved at a very low speed ($V_{maxWR-2}$ = 0.03 m/s) and could not rotate as naturally as real rats. These disadvantages led only to preliminary experimental results and did not suffice to prove the research hypotheses stated. Given this lack of a suitable experimental bio-mimetic robot platform, we considered it is essential to develop a robot that can sufficiently imitate the movements of a rat during interaction. We built on the experiences gained from previous robot prototypes, to propose the integration of the advantages of WM-6 ($V_{maxWM-6}$=1m/s) [45] and WR-2 to develop a wheel-legged robot, called WR-3 (Figure 3.14) [91], which is capable of higher movement speed and better behavior imitation.

In previous research, several bio-mimetic, wheel-legged robots have been designed for moving on uneven terrains [92], [93]. In [92] a hybrid robot called Wheeleg has been designed to analyze the principal capabilities of a wheel-legged robot to traverse through rough terrain. It has two pneumatically actuated front legs and two rear wheels, which are actuated independently. WR-3 is developed with high motion performance to perform SIT with a real rat realistically.

### 3.4.2 Modeling and DOF configuration

In order to perform similar social behaviors as rats, the motion mechanism of the robot was designed on the basis of the behavioral model shown in Figure 3.15. The reproduction of social behaviors mainly depends on the motion of the animal's legs, neck and waist.

If the movements involved rearing and rotating behaviors can be realized, social behaviors such as mounting (very similar to rearing) and grooming (very similar to rotating) is considered to be also possible. Therefore, based on pictures of the anatomy of a rat, the joint angle limits of rats during rearing and rotating actions can be determined. These angle limits are to be used as the key reference of the joint design concept of the proposed robot.

Similarly to WR-2, for the DOF arrangement of WR-3, moving motion of a rat is recorded by a video camera, and a stick diagram is obtained using visual analysis. The results of this
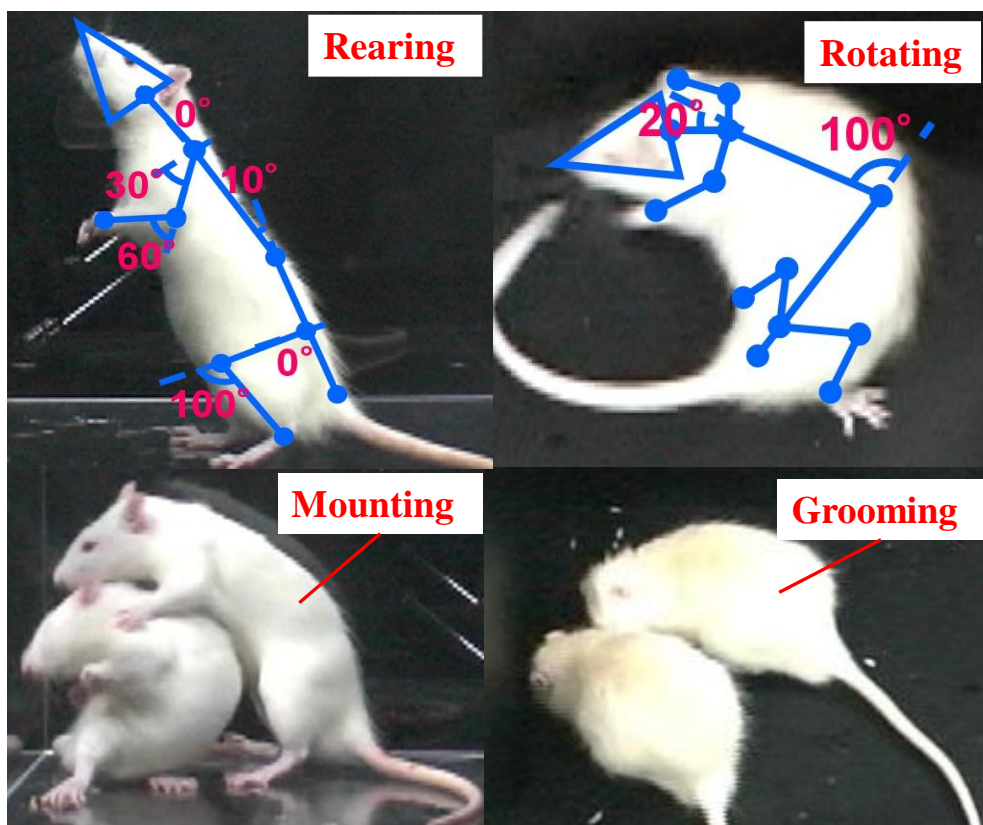
Figure 3.15 The behavioral model of the rat. The mounting and grooming behaviors of rats are quite similar to rearing and rotating behaviors respectively
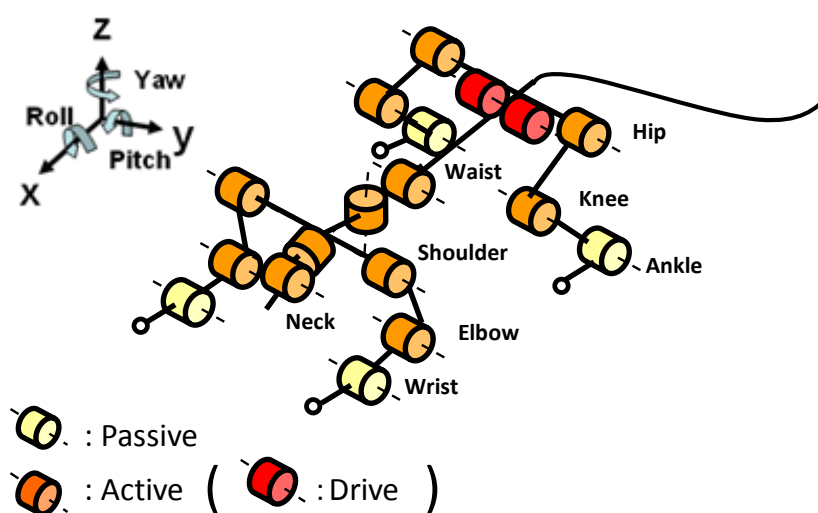


Figure 3.16 From the behavioral model and walking gait of an adult rat, the DOF arrangement and kinematical model of WR-3 is proposed

analysis demonstrate, that each limb can be represented as two active DOFs (one pitch joint at the shoulder / hip and one pitch joint at the elbow / knee) and one passive DOF (one pitch joint at the wrist / ankle has been designed to make the robot capable of better mimicking the shape of a real rat). Rats have a flexible spine and they can bend their body when they rear by legs or groom. We consider that these motions can be represented by a 2-DOF waist joint (pitch joint and yaw joint).

If the robot is able to move quickly, it should be capable of following the living rat. However, it is quite difficult to move quickly when the robot is actuated merely by a legged locomotion mechanism [94]. Furthermore, from observing the behavior of rats we consider, that their motion can be roughly divided into two phases: movement (from one larger scale location to the next) and interaction. During the movement phase, the wheeled locomotion mechanism composed of two wheels, can drive the robot to follow the rat at high speed. After moving close to the rat, the legged locomotion mechanism is used during the interaction of the robot with the rat. The wheeled and legged locomotion mechanisms are combined, to give optimum movement capabilities to the rat-like robot, in order to allow for fast movement and natural interaction. The muscle and skeleton structure of the robot can be represented by the DOF arrangement and kinematic model, which is shown in Figure 3.16.

## 3.4.3 Mechanical Design

### A. Actuator Determination

DC motors with rotary encoders are used to actuate the wheel-legged locomotion mechanism with consideration to miniaturization and feedback control. The output torque of each motor depends on the required force and torque in each DOF of WR-3. Therefore, we calculated force and torque of every joint based on the force and kinematics analysis as described in the following paragraph.

The main driving mechanism, the DC motors installed to actuate the wheels, should be strong enough to satisfy the power requirements of the robot. The DC motors should output enough torque to overcome friction ($T_f$) and accelerate the robot ($T_I$). If the robot is supported only by two wheels (during rearing behavior), one DC motor should output the maximal output torque ($T_{max}$). The equations that we used for this calculation are shown below.

$$T_{\max} = T_f + T_I \tag{3.4}$$

$$T_f = \frac{f}{2} \bullet \frac{D}{2} = \frac{\mu mg}{2} \bullet \frac{D}{2} \tag{3.5}$$

$$T_I = I \bullet \ddot{\theta} = \frac{1}{2} m(\frac{D}{2})^2 \bullet \ddot{\theta} \tag{3.6}$$

Here, $f$, $D$, $\mu$, $m$, $g$, $I$, $\ddot{\theta}$, denote the static friction force, wheel diameter, static friction coefficient, robot mass, the gravity constant, moment of inertia and angular acceleration respectively. As the parameters $\mu$ and $\ddot{\theta}$ should be predetermined to guarantee that the robot can interact with rats under experimental conditions. Afterwards, the Tmax can be derived from Eq.3.4 ~ Eq.3.6 numerically.

The legged locomotion mechanism is used to perform interaction when the robot is situated close to the living rat. The motor torque and forces that are required to drive the leg mechanism are quite small. Therefore, while designing this mechanism we were able to put emphasis on the compactness of the concept. The pitch joint of the waist of the robot (for rearing behavior) is actuated by an 8 V servo motor. To allow for the rotating action we chose a 5V servo motor to control the yaw joint of the robot body. In order to decrease the space consumption, shape memory alloys (SMA) were installed as actuators to control the neck of the robot to make it able to move in the direction of pitch and yaw respectively.

### B. Wheels and legs

In case of the wheeled mechanism, a timing belt has been used to transfer the torque from the motor to each wheel. In order to allow the robot move in a stable way, a three-legged support structure composed by two wheels and a caster were installed near the forelegs.

According to DOF configuration, each leg consists of 2 active DOFs. One of these is configured in the shoulder / hip as pitch joint. The other one is embedded in the elbow / knee as pitch joint. The wrist / ankle joint have been added as passive DOF to mimic the shape of a rat's leg. Figure 3.17 demonstrates the 3D design scheme of the left foreleg.
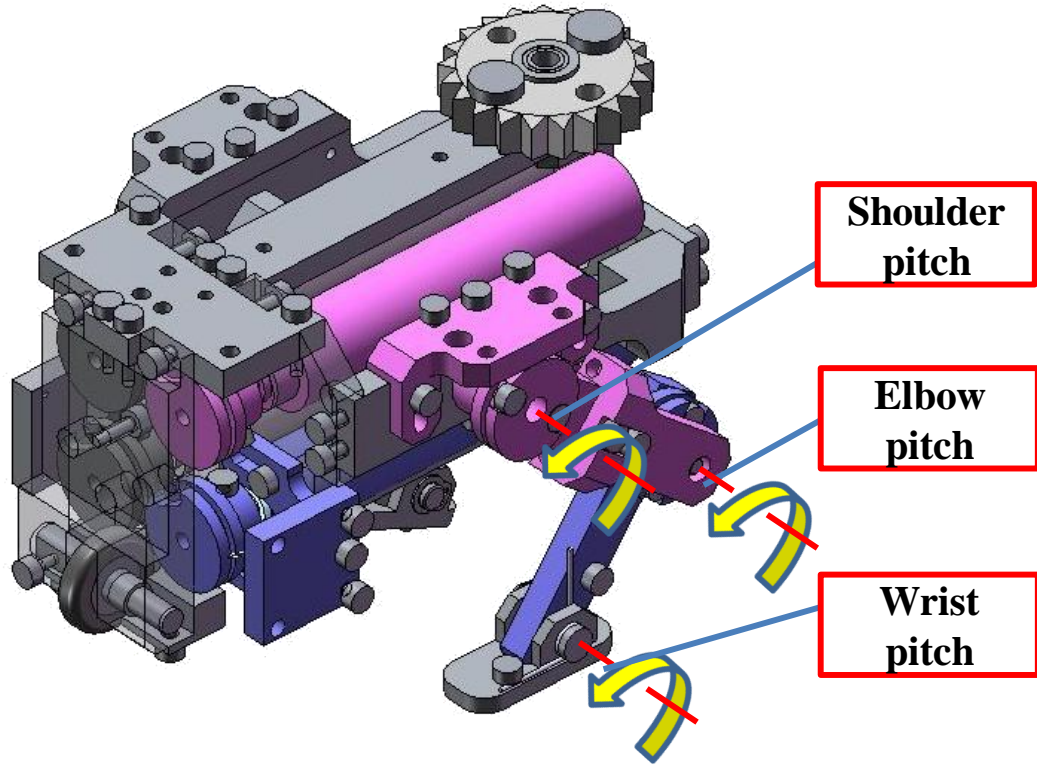
Figure 3.17 Illustration of the mechanical design of the left foreleg. It consists of 2 active DOFs: pitch joints of the shoulder and the elbow. 1passive DOF: pitch joint of the wrist
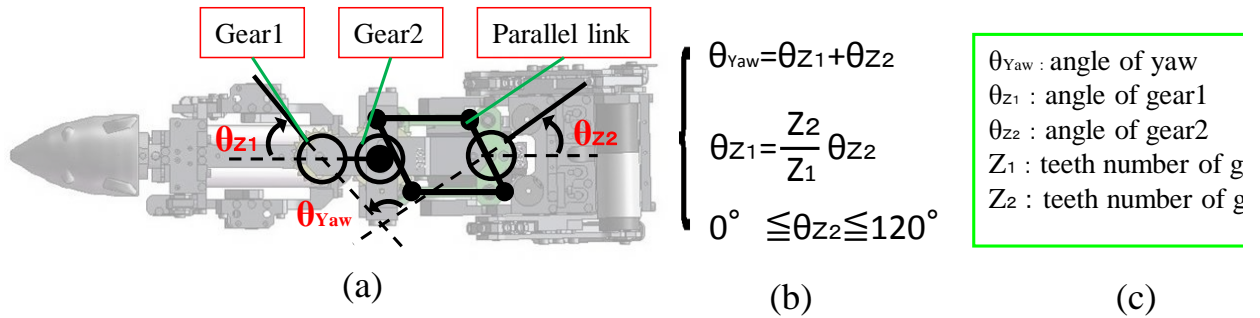


Figure 3.18 The movable angle range of the waist yaw direction: (a) The mechanism of the yaw joint of the waist consists of two gears and a parallel link. (b) Based on the proposed equations, the range of $\theta_{Yaw}$ can vary accordingly with gear ratio $Z1/Z2$. (c) The definition of these abbreviations
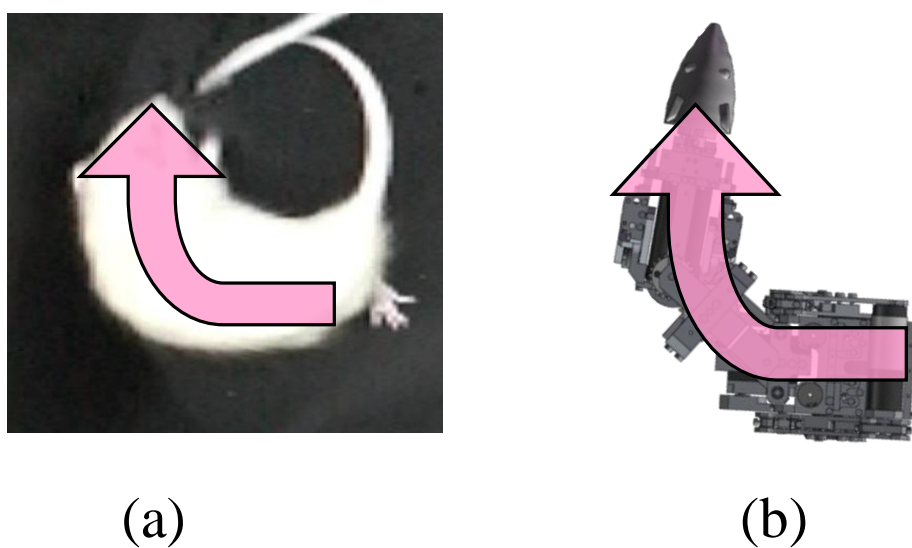
Figure 3.19 The rotating comparison between a rat and WR-3
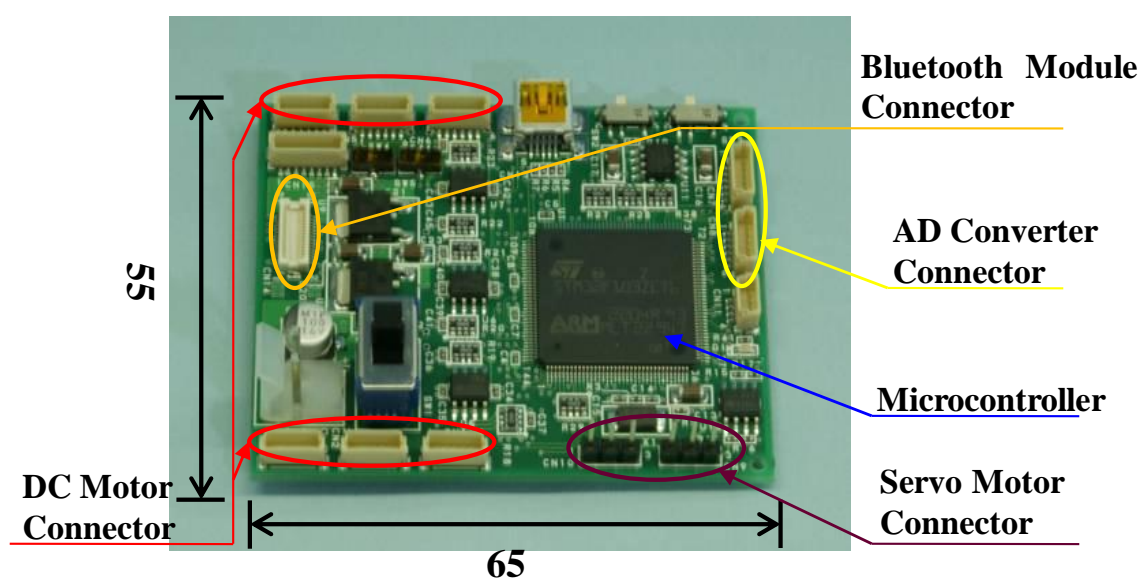


Figure 3.20 Controller circuit board of WR-3, a microcontroller, that is STM32F103ZE6T and 3 motor drivers (each impels two DC motors) are embedded in this circuit board. (Number unit: mm)

### C. Waist and Neck

The rearing and grooming behaviors are implemented using the yaw and pitch joints of waist and neck of the robot body (see A of this section).

When a rat grooms, strong variations of the body rotation angle occur. The mechanical design of the robot should be built to allow the robot to perform such movements in imitation of a real rat. As shown in Figure 3.18, the angle range of the waist yaw DOF can be much larger than 120 degrees (depending on the gear ratio Z1 / Z2) that makes the robot capable of realistic grooming behavior. To reproduce natural rotation behavior, two gears and a parallel link were built into the robot's waist as shown in Figure 3.18(a). As displayed in the

simulation diagram Figure 3.19, given the described mechanical configuration, the robot can rotate with a degree of dexterity that is similar to a real rat.

### 3.4.4 Control Architecture

A microcontroller unit (MCU) module and wireless data transmission module are embedded in WR-3. The robot is controlled using a PC that communicates with the MCU of the robot through wireless communication.

To control the DC motors and servo motors of WR-3 we designed a special controller module. Figure 3.20 displays the developed motor driver circuit board. Using this module 6

DC motors and 2 servo motors can be controlled simultaneously using a ST Microelectronics MCU STM32F103ZE6T. Totally 10 DC motors and 2 servo motors are used in WR-3. To control a total of 10 DC motors and 2 servo motors, we equipped WR-3 with two of the described controller boards.

As previously described, the WR-3 motion includes chasing, rearing, grooming and mounting behaviors. An off-line pattern generator calculates the data that is required to produce these motion patterns. This data is preloaded to WR-3 as packages that contain time-line data of each joint angle for each behavior mode. The MCU controls the angle of each joint based on this pattern information, when it receives instructions from the control PC. As shown in Figure 3.21, each DC motor is controlled by a closed loop servo-control system that consists of a position, speed and current control loop.
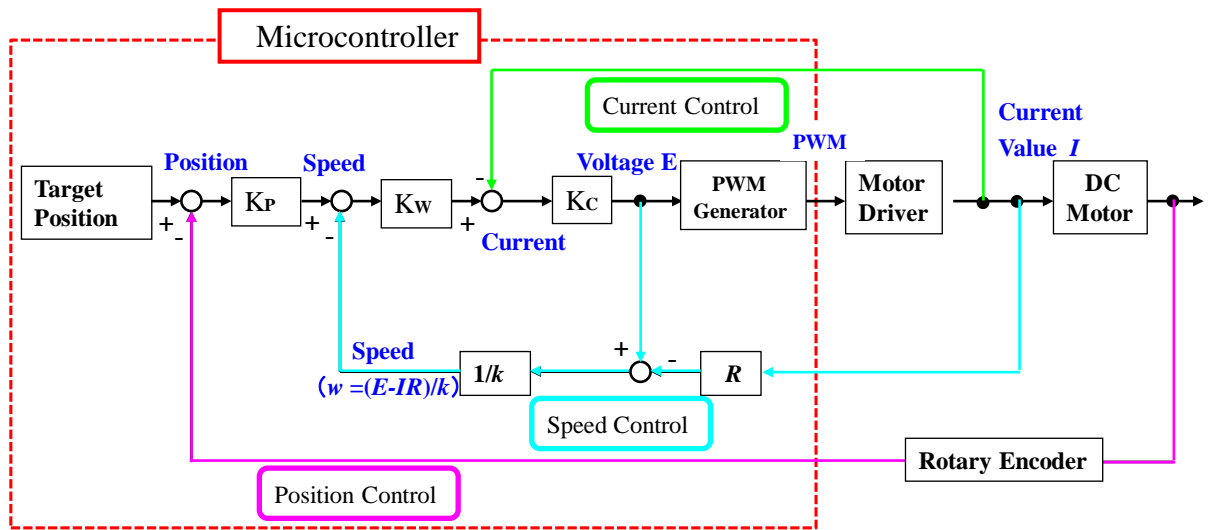
Figure 3.21 Schematic diagram of closed loop control system: position control ($K_P$: position gain) and speed control ($Kw$: speed gain) and current control ($K_C$: current gain) have been used to accurately control the output of DC motors

## 3.4.5 Performance Evaluation Results

To evaluate the movement performance of WR-3, we performed a locomotion speed test. After 5 tests, we calculated an average maximal walking speed of $V_{maxWR-3} = 1$ m/s. From the observation of the walking and running speed of a living rat, we consider that the minimum speed required to follow a living, mature rat is $V_{mint} = V_{rat} = 0.45$ m/s. As a result, the speed of WR-3 is sufficient to perform SIT in view of locomotion speed. Table 3.2 shows a comparison between the maximum movement velocity of WR-3 and other robots.

We evaluated the motion performance of WR-3 during rearing and rotating actions as well. Using a video camera, for each action displayed in Figure 3.22, we captured 3 images of WR-3. Different actions were assigned to angle values as described in Figure 3.22. We controlled WR-3 to perform rearing and rotating actions 3 times respectively. As soon as WR-3 reached the target gesture (0º, 30º, 60º for rearing action, 0º, 35º, -70º for rotation action), we recorded the elapsed time. At the end of the experiment we calculated the average elapsed time for each gesture. Each value is the average of three elapsed time values from the test results. We can see from the results that WR-3 could perform these actions quite similarly to rats regarding performance time values and gesture reproduction accuracy. According to Figure 3.15, when the robot is able to perform a rat's rearing and rotating actions, the mounting

and grooming actions can be physically feasible. Consequently, we consider WR-3 to be capable of mimicking various social actions of a rat (chasing, rearing, grooming, mounting etc.)

Table 3.2 Locomotion speed comparison between different robots

| Speed parameter | Value(m/s) |
| --- | --- |
| $V_{maxWR\text{-}1}$ | 0.02 |
| $V_{maxWR\text{-}2}$ | 0.03 |
| $V_{maxWM\text{-}6}$ | 1 |
| $V_{maxWR\text{-}3}$ | 1 |
| $V_{mint}$ | 0.45 |
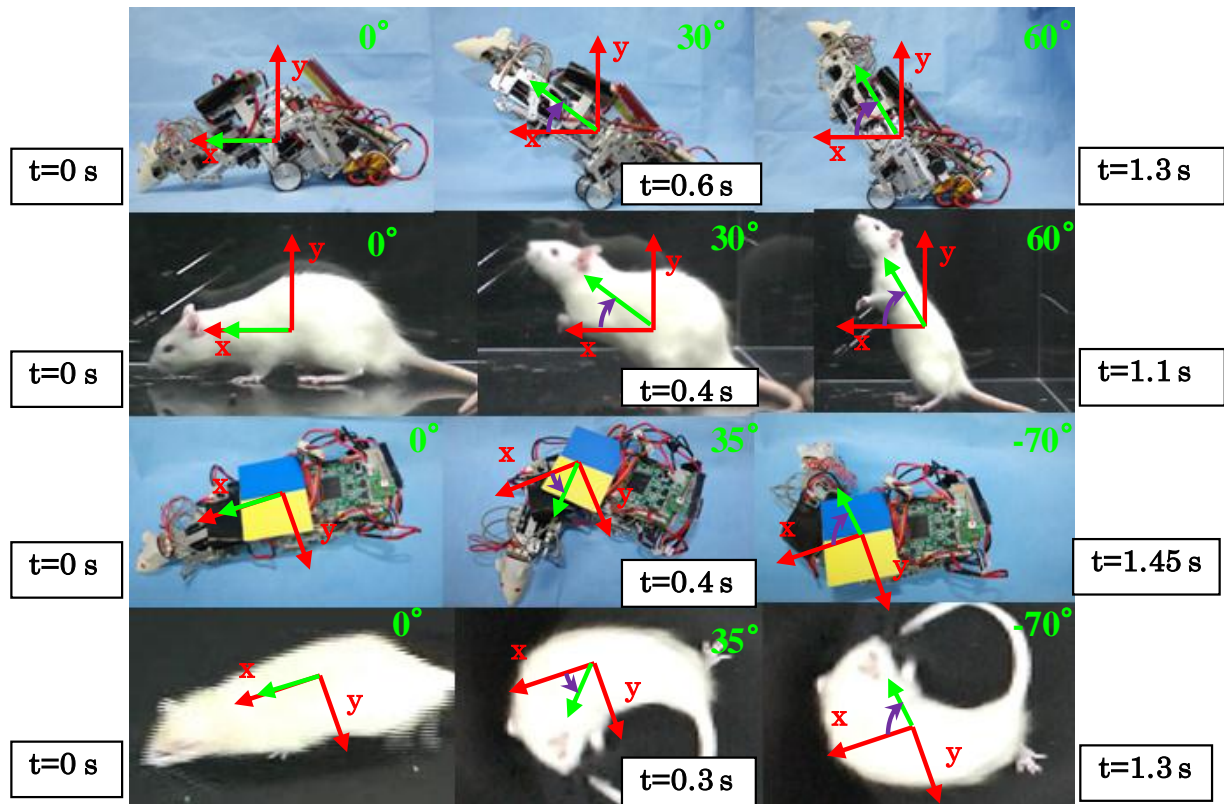


Figure 3.22 Capture pictures of WR-3's social behaviors. Top two rows: WR-3 and a rat act "rearing". Bottom two rows: WR-3 and a rat act "rotating". According to the time and angle labeled in the figure, WR-3 could act rearing and rotating similarly as rats

To confirm the importance of shape imitation, the rat's preference to WR-3 has been eval-

uated by the experiments introduced in Appendix A. Likewise, these experiments can be used to evaluate the degree of preference that is induced to the rat by the robot. In addition, preliminary SIT between WR-3 and living, mature rats has been conducted, please refer to the detail described in Appendix B.

# 3.5 Multi-bendable Mobile Robot: WR-4

### 3.5.1 Design Requirements

As described in the preceding section, WR-3 was developed with higher moving speed and better imitation behaviors by integrating the advantages of wheeled and legged mechanism. However, experiment results showed that limited moving range of waist and neck of WR-3 caused linear bend posture, which is different with the curved bend posture of rats. On occasion the locomotion of WR-3 appears drastically unstable. Given this lack of a suitable experimental bio-mimetic robot platform, we considered it is essential to develop a robot that can sufficiently imitate the behaviors of a rat during SIT. Building on the experiences gained from previous robot prototypes, to propose a multi-bendable body, which is capable of moving more steadily and bending more similarly as living rats, we developed an improved animaloid robot WR-4 [95] as shown in Figure 3.23.
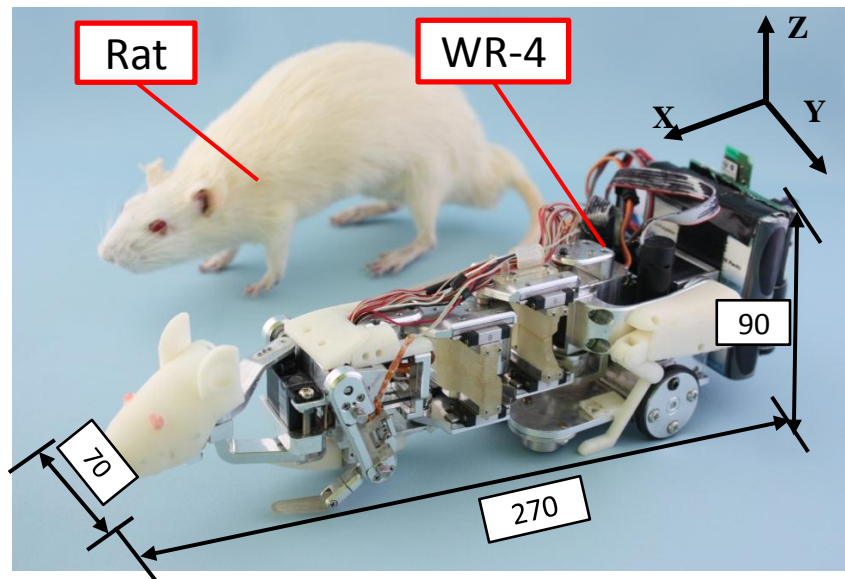


Figure 3.23 The shape of the mobile robot WR-4 and a mature stuffed rat. (Number unit: mm)
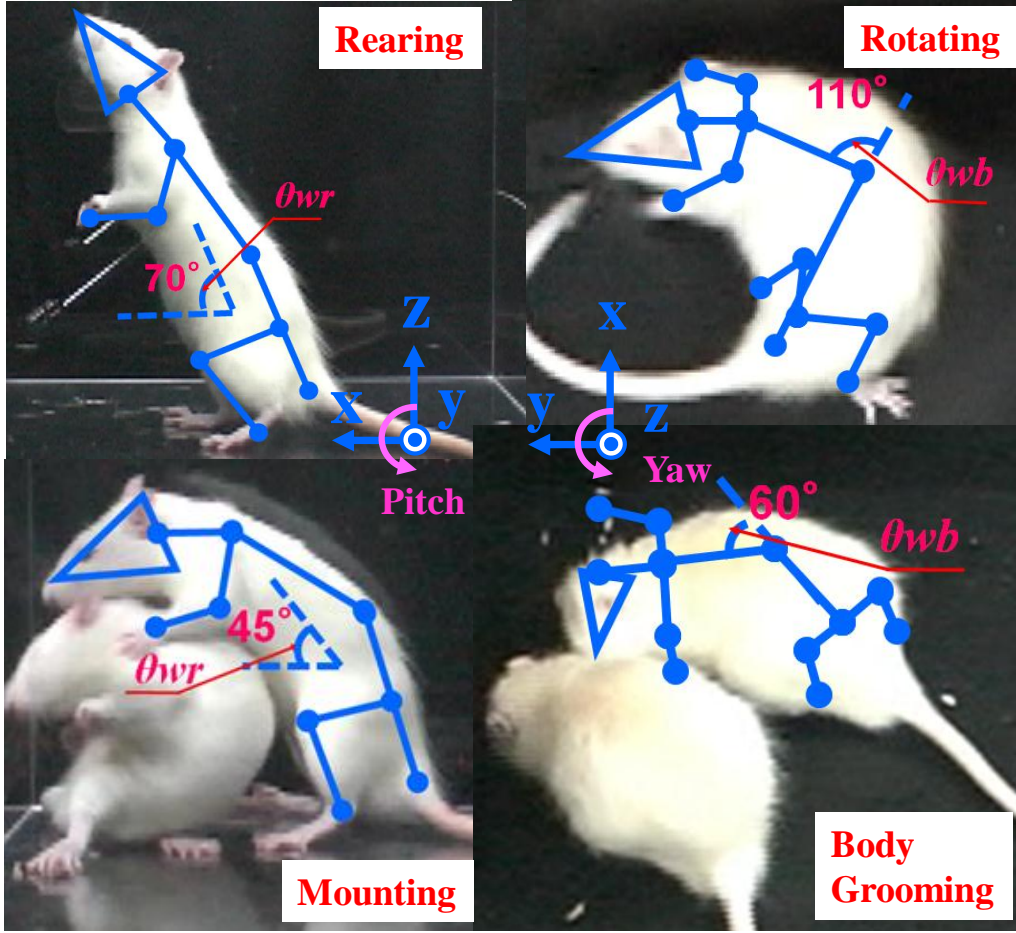
Figure 3.24 The behavioral model of rats. The maximum of $\theta_{wr}$ and $\theta_{wb}$ respectively correspond to the movement limits of rearing and rotating behaviors

## 3.5.2 Modeling and DOF Configuration

The most important performance of this robot lies on the behavior imitation of living rats. To better meet the requirements, robot skeleton was determined on the basis of the behavioral model of rats as shown in Figure 3.24. We can see that the social behaviors of rats are mainly implemented by the neck and waist besides limbs. In the view of movement limits, if the robot can act rearing and rotating behaviors, the social behavior as mounting (considered nearly as a kind of rearing) and body grooming (considered nearly as a kind of rotating) will be physically feasible. The movement limits of rearing angle $\theta_{wr}$ (Note that the sign of $\theta_{wr}$ is opposite to the pitch) in the x-z plane and bending angle $\theta_{wb}$ in the x-y plane can be determined in advance according to Figure 3.24 (the maximum of $\theta_{wr}$, $\theta_{wb}$ are approximately 70°, 100°).
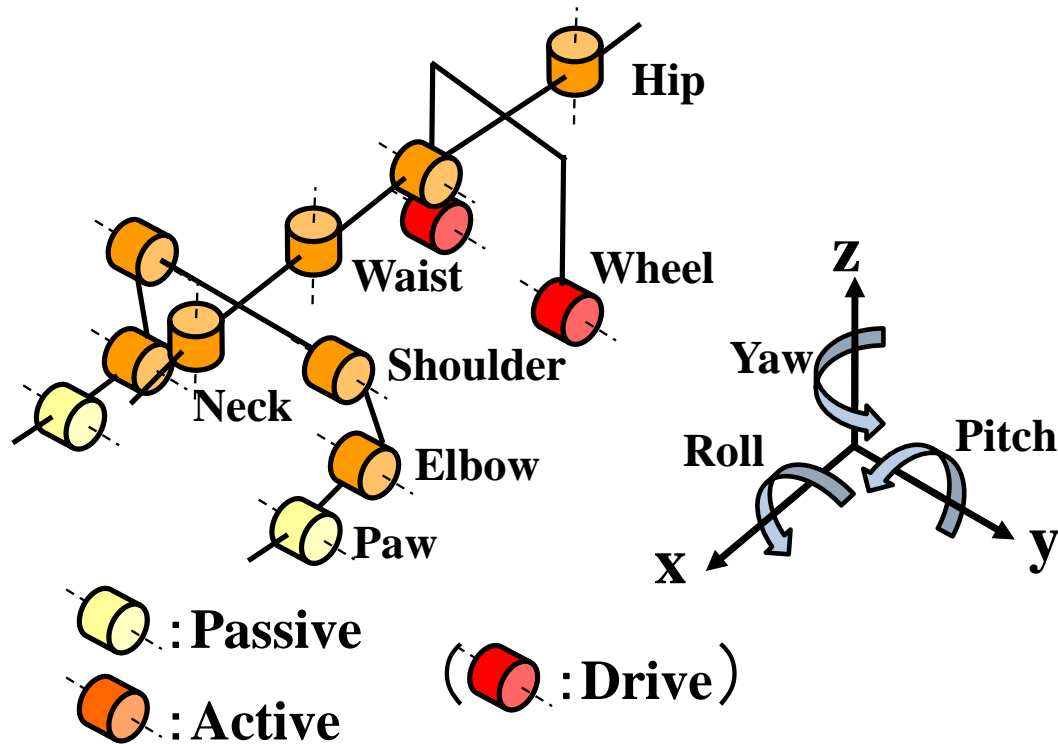
Figure 3.25 DOF arrangement of WR-4 is determined on the behavioral model, anatomy pictures and motion analysis of rats. The two wheels configured 1 DOF respectively are for locomotion, and the other 8 active DOFs integrated together allows mimicking the social behaviors of rats.

These two parameters are used as the key reference to design joints and select actuators.

The robot needs to be equipped with high locomotion speed to follow running rats. However, in general the robot drived only by legged mechanism fails to achieve high locomotion speed. Based on the observation of rat actions, their motion can be roughly divided into two phases: moving and interaction. In the moving phase, the wheeled mechanism composed of two wheels, exerting considerable forces and torques, drive the robot to catch up with the rat in a short time. After moving near the rat, the forelegs drived by legged mechanism, waist and neck serve to make robot interact with the rat. Besides, inspired from the rat anatomy pictures [96], we consider that the skeleton structure of WR-4 can be represented by the DOF arrangement as depicted in Figure 3.25. WR-4 consists of 10 active DOFs (two 1-DOF wheels for locomotion, one 2-DOF forelegs for interaction, one 1-DOF neck for swing, one 2-DOF waist for rearing and body grooming and one 1-DOF reserved for tail) and 2 passive DOFs in

the paws.

### 3.5.3 System Design

The waist, foreleg, and neck of WR-4 have changed significantly to address the inadequacies of WR-3 [91]. Thus these 3 parts are the focus of mechanical design for WR-4.

*A. Waist*

The waist of WR-4 configured with 2 DOFs is actuated by servo motors: one DOF around pitch axis serves as the driver for acting rearing behavior, the other one around yaw axis serves as a drive axle of the multi-bendable 6-bar linkage mechanism. Based on the mechanical geometry and design view of the waist endowed with the 6-bar linkage mechanism illustrated in Figure 3.26 The waist is endowed with a multi-bendable 6-bar linkage mechanism., the mathematical relationship between the waist bending angle $\theta_{wb}$ around yaw axis and the servo motor output angle, that is the rotation angle of drive axle $\theta_i$ can be derived by the following two equations.

$$e = \frac{l_2}{l_1} \tag{3.7}$$

$$\theta_{wb} = 3\theta_i + \arcsin(\frac{2e(1 - e \cdot \cos\theta_i)\sin\theta_i}{1 + e^2 - 2e \cdot \cos\theta_i}) \tag{3.8}$$

Note that $l_1$ (here is 35 mm) is the length of longer links (Link $L_2$, $L_3$, $L_4$, $L_5$), $l_2$ (here is 5 mm) the length of the shorter links (Link $L_1$, $L_6$, as well as the distance between Joint $J_1$ and Joint $J_2$). As the output angle range of the drive axle is $-45^\circ \leq \theta_i \leq 45^\circ$, the range of waist bending angle is calculated as $-130^\circ \leq \theta_{wb} \leq 130^\circ$.

As shown in Figure 3.26 The waist is endowed with a multi-bendable 6-bar linkage mechanism.(b), there are four linear guides that are used for the link $L_2$, $L_3$, $L_4$ and $L_5$ respectively. The two linear guides used for $L_2$ and $L_3$ are connected together, as well
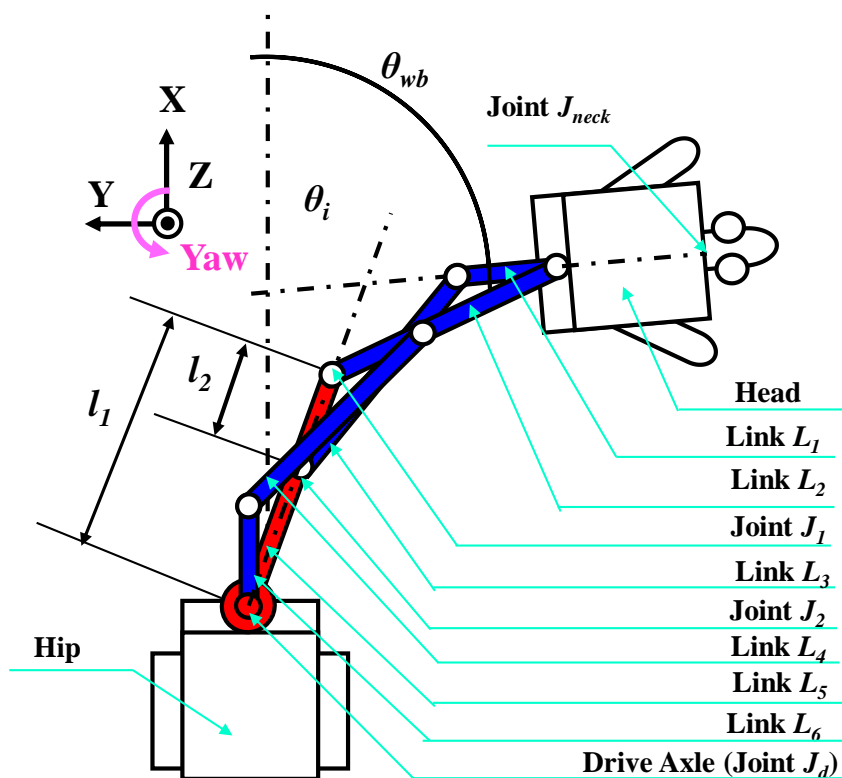
(a) The geometric characteristic between $\theta_i$ and $\theta_{wb}$
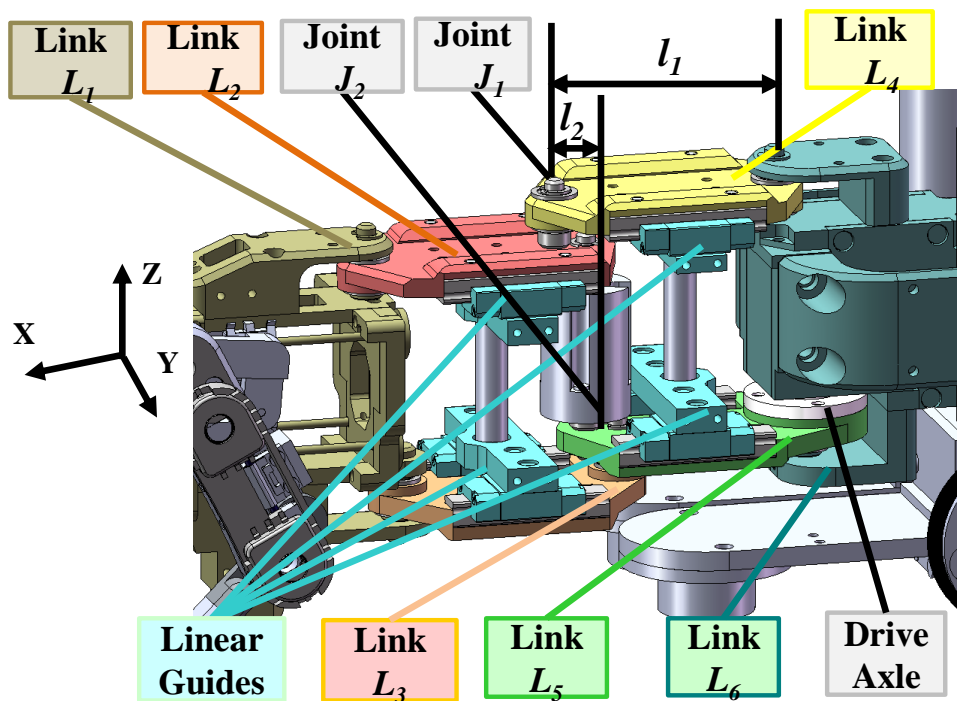


(b) Mechanical design of the waist

Figure 3.26 The waist is endowed with a multi-bendable 6-bar linkage mechanism.
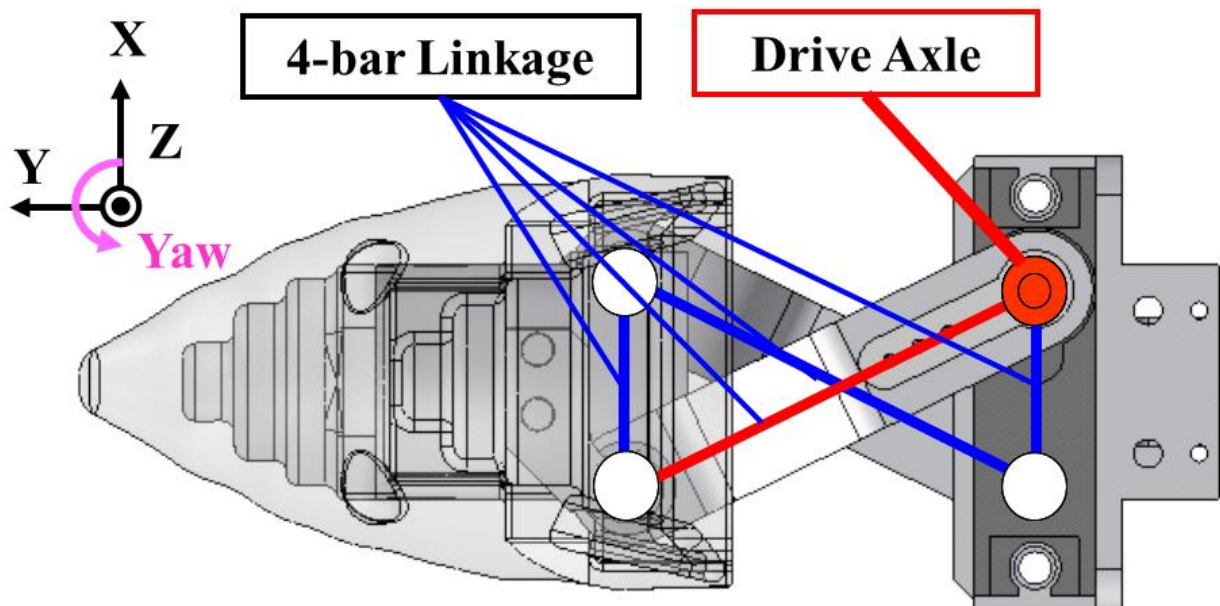
Figure 3.27  Mechanical design of the neck. The 4-bar linkage mechanism in the neck, makes WR-4 able to mimic the bent neck posture of rats
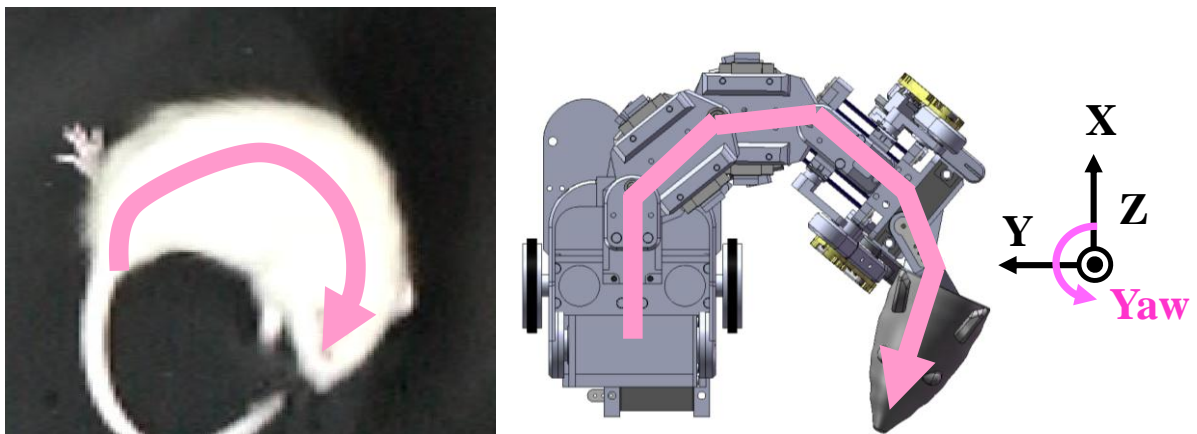


Figure 3.28 The bent waist and neck posture comparison between a rat and WR-4. WR-4 can rotate in greatly curved posture, similarly as living rats

as the two linear guides used for $L_4$ and $L_5$. As a result, the intersection between all the links allows to avoid singular point, which easily occurs when all the links overlap to form a
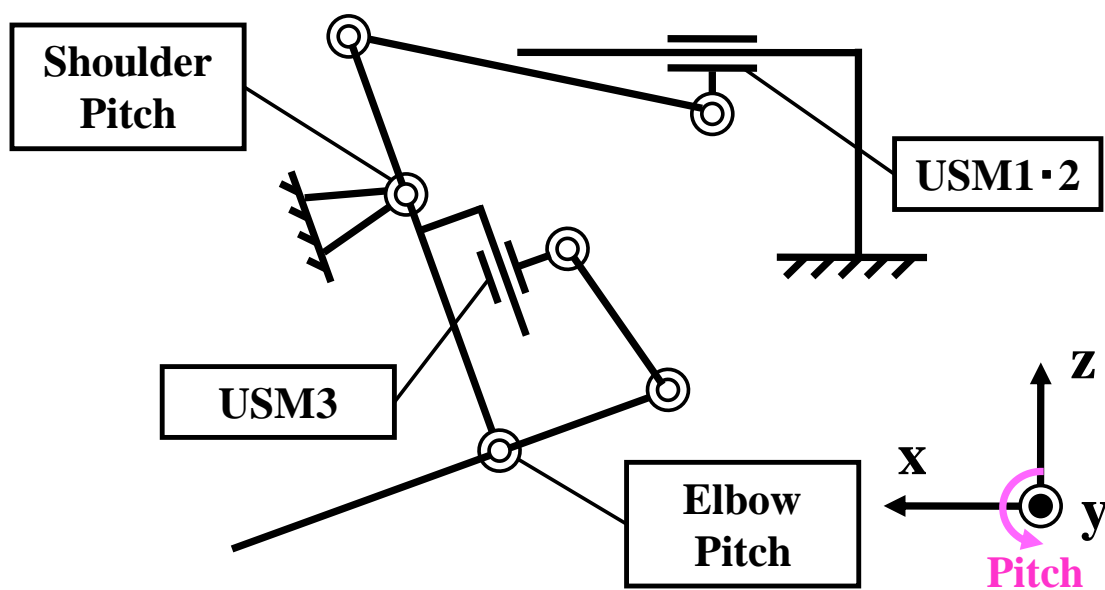
(a) Mechanism principle of the left foreleg
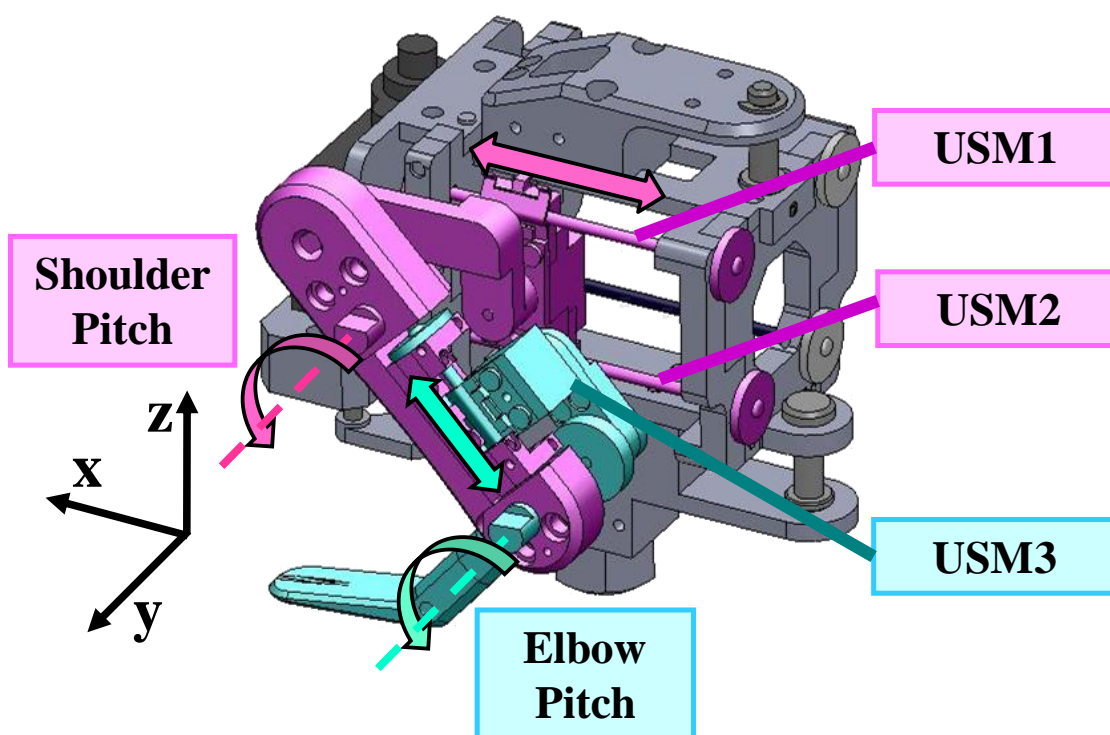


(b) Mechanical design of the left foreleg

Figure 3.29 Mechanism principle and mechanical design of the left foreleg

straight line, in other words when the $\theta_i$ is 0. Therefore, only a linkage mechanism in the waist makes WR-4 achieve to bend to both left and right directions.

### B. Neck

One DOF in the Yaw axis is arranged to achieve the neck rotation driven by one easily controlled servo motor. As shown in Figure 3.27, the adoption of 4-bar linkage mechanism in the neck, makes WR-4 able to mimic the curved posture of rats when bending neck. The upper body of WR-4, integrating with the neck and the multi-bendable waist described in part A of this section, guarantees better imitation of the rotating behavior of rats. As shown in Figure 3.28, the waist and neck are able to bend in curved posture, achieving to better mimic the rotating behavior of rats.

### C. Foreleg

Figure 3.29 shows mechanism theory and mechanical design of the left foreleg (The right foreleg is same as the left one when taking into account the symmetry). Actions of the forelegs are achieved by using slider crank mechanism drived by USM (ultrasonic motor). As shown in the Figure 3.29 (b), to guarantee enough power, two motors: USM 1 and 2 placed parallelly in the body drive the left shoulder joint to rotate around pitch axis. USM 3 placed in the upper arm drives the left elbow joint to rotate around pitch axis. The adoption of USM significantly contributes to achieve the lightweight upper body of WR-4. Actually, the whole weight of WR-4 (0.85 kg) is quite lighter than that of WR-3 (1 kg). Furthermore, the lightweight upper body of WR-4 greatly contributes to quicker and more stable rearing behavior.

### D. Control Architecture

WR-4 is controlled by a PC via wireless communication with the microcontroller (model number: STM32F103ZE6T) manufactured by STMicroelectronics company. The motor driver circuit board described in [91] is able to control 6 DC motors and 2 servo motors. As the servo motors and USM are drived by PWM generated by the microcontroller, similarly to the DC motors. Thus we use the same driver circuit board of WR-3 to control 2 DC motors, 4 servo motors and 6 USM (as each shoulder is drived by 2 USM, the total number of USM need to be controlled by the microcontroller is actually 4.) of WR-4. The behaviors acted by WR-4

mainly include chasing, rearing, rotating, body grooming, mounting, etc. These behavior patterns are generated based on the behavior learning of rats in the form of motion parameter packages. These motion parameter packages are preloaded in the microcontroller as time-line data of each joint angle. After receiving the instructions from the master PC, the microcontroller controls the angle of each joint based on the time-line motion parameters.

### 3.5.4 Performance Evaluation Results

To verify proposed specifications, the motion performance evaluation of WR-4 was conducted. The range of waist bending angle $\theta_{wb}$ was measured between -130° and +130°, proving Eq.3.8. The maximum angle that WR-4 could rear ($\theta_{wrm}$) is 80°. These two maximum angles meet the specifications of mimicking rearing and rotating behaviors of rats as shown in Figure 3.24. The maximum locomotion speed of WR-4 is 1 m/s, fully meeting the speed to chase running rats (in general the speed of a running rat is no more than 1 m/s).

When acting the rearing and rotating behavior, although the movement range of WR-4 are $0° \leq \theta_{wr} \leq 80°$ and $-130° \leq \theta_{wb} \leq 130°$ respectively, in general the rats rear to 60°, and rotate to ±100°. To effectively and completely obtain the rats behavior data, the maximum angle of rearing and rotating behavior are set as 60° and 100° respectively in the following motion performance evaluation. For the rearing behavior (in the x-z plane), the least time-consuming of WR-4 rearing to 10°, 20°, 30°, 40°, 50°, 60°, from initial position that is 0°, were recorded respectively. In the case of acting rotating behavior (in the x-y plane), we recorded the least time-consuming in the angle of ±20°, ±40°, ±60°, ±80°, ±100°. Every test was conducted 3 times repetitively, and the results were averaged. We have observed totally videotaped behavior data of 5 9-week rats. The video clips related to rearing and rotating behaviors were repeatedly observed and measured. For each videotaped rat behavior, we extracted the fastest implementation of rearing and rotating behaviors as the final results respectively. As shown Figure 3.30, when reaching the predetermined maximum angles (rearing: 60°, rotating: ±100°), WR-4 could act both rearing and rotating behavior approximately 0.1s quicker than mature rats. The excellent motion performance reveals that WR-4 achieved good imitation of rearing and rotating behavior in terms of speed and movable range, compared with rats.
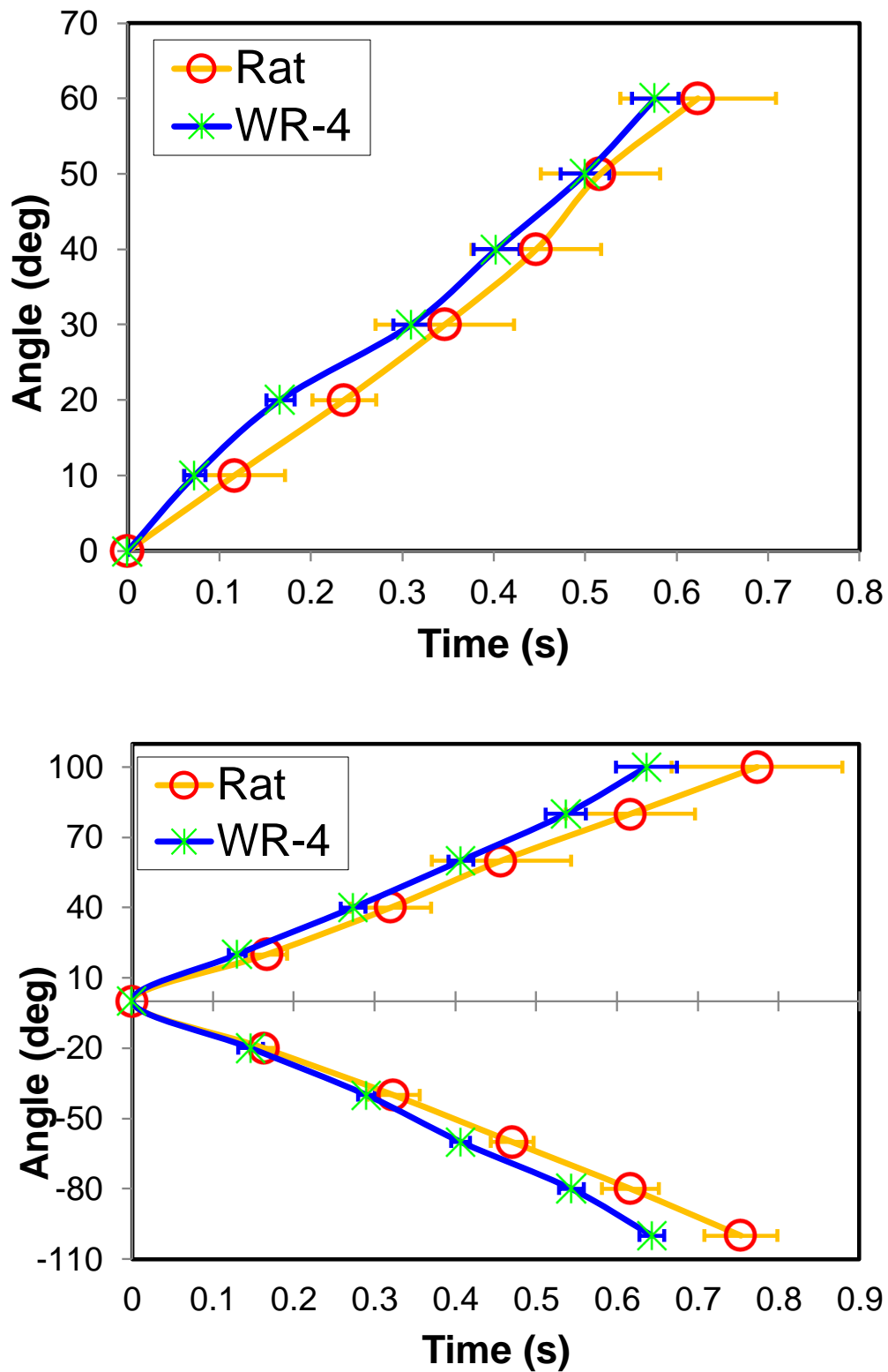
Figure 3.30 The motion performance evaluation results of WR-4 and rats acting rearing (top) and rotating (bottom) behaviors

# 3.6  Discussion

This chapter introduced the design and development of WR-2, WR-3 and WR-4 robots, the performance of which will be discussed below respectively.

## 3.6.1 Comprehensive Evaluation of WR-2

WR-2 is much more similar to an adult rat in shape and dimension than its former version WR-1, and is able to walk as real rats owing to the quadruped walking mechanism. Furthermore, it is capable of mimicking rotating behavior of rats. WR-2 can be used for the study of rat walk gait. Even WR-2 may be promising for the research on the walk gait of other tetrapods. However, according to the performance evaluation experiments, the joint rigidity of WR-2 appeared a little low attributing to the use of wire and outer-tube driving mechanism, and therefore its walking speed is sometimes slow and uneven. Occasionally motion instability occurred as well. Thus, in further research, the author made an attempt to improve the motion stability and robustness of WR-2. The author would also develop a new robot furnished with a lightweight body, further miniaturization and better similarity of rat appearance for next stage research.

## 3.6.2 Comprehensive Evaluation of WR-3

Regarding WR-3, locomotion speed test showed that it could move at a maximum speed of 1m/s, guaranteeing enough capability of chasing the living rats. Motion performance evaluation tests show that WR-3 is capable of mimicking social actions (chasing, rearing, grooming, mounting etc.) quite similarly to rats regarding performance time values and gesture reproduction accuracy. The results of preliminary SIT with real rats confirmed that WR-3 is able to inspire actions of a rat to some degree. Although the movement of WR-3 appears unstable, it is promising for the interaction experiments to develop RMMD. However, the preference evaluation described in Appendix A showed that the shape design of WR-3 is still improvable.

## 3.6.3 Comprehensive Evaluation of WR-4

For the design of WR-4, its waist endowed with the multi-bendable 6-bar linkage mechanism makes the robot able to rotate around $\pm130^{\circ}$ horizontally, meeting the required movement

range. The integration of the multi-bendable waist and the 4-bar linkage mechanism in the neck achieves the bending posture as living rats, allowing the imitation of behavior such as rotating. Furthermore, the USM used to drive forelegs greatly reduce the weight of upper body, resulting in quicker acting of rearing behavior. The evaluation tests on implementation performance of rearing and rotating behavior were conducted. The test results show that WR-4 could act both rearing and rotating behavior about 0.1s quicker than mature rats when reaching the predetermined maximum angles. The quicker acting of rearing and rotating behavior reveals that WR-4 is endowed with almost the same motion performance of living, mature rats. Preliminary SIT results reveal that the frequency of rearing behavior in rats was decreased after WR-4 reared. The increased rearing behavior in rats suggests that WR-4 is able to inspire rearing behavior of rats to some extent, as well as to alter the activity of rats.

In addition, better sensitivity of the driving system makes WR-4 able to follow the rat softly in the robot-rat interaction. Therefore, another potential application for WR-4 involves creating friendly relationship with rats.

# 3.7 Summary of this Chapter

This chapter presented the hardware design of rat-like robots. All the robots have been developed based on the methodologies. For instance, the body framework and DOF configuration are determined by the observation and analysis of the behavior and walking gait of rats. The design process and performance evaluation were introduced in detail in this chapter. In summary, the characteristics of each robot can be concluded as the following.

1) WR-2 is much more similar to an adult rat in shape and dimension than its former version WR-1, and is able to walk as real rats owing to the quadruped walking mechanism. However, the motion stability and robustness of WR-2 need to be improved.

2) Given the advantages of hybrid wheel-legged driving system, WR-3 is able to move as fast as mature rats and to interact with rats naturally. This robot is capable of mimicking rearing, rotating, grooming and chasing behaviors. But the shape imitation of rats is still insufficient, result in low preference from rats.

3) Compared with WR-3, great progresses were made for WR-4 in body miniaturization and bend gesture of waist and neck. Performance evaluation tests show that WR-4 could act both rearing and rotating behaviors similarly as real rats. Furthermore, WR-4

is able to move stably and softly, solving the shortcomings of WR-3.

4) In further work, by developing new motion patterns and combining the current motion patterns, we would like to enable the robot able to do more new types and variations of social behaviors. Through the analysis of experimental results, we can find out more behaviors that how to specifically influence the behaviors of rats (e.g. changing activity, inducing certain social behavior, etc.). Consequently, we can let the robot mimic such kind of social behaviors that have stronger influence on rats to obtain effective results of the SIT. Finally, as a long-term objective, we would like to develop a robot that can automatically perform SIT with rats and which conveys a completely natural impression on living rats.

# Chapter 4

# Recognition System and Behavior Generation

## 4.1 Introduction

### 4.1.1 Background

For the analysis of robot-rat interactions and the operation of remote-controlled robots, tracking of robot and rats is vital and is usually done via digital video cameras connected to a computer. Based on the video camera, the number and duration of social behaviors (e.g., rearing, grooming) rats acted can be measured to analyze the stress of rats, and the robot is able to generate corresponding behaviors to interact with rats.

In fact, it has become an increasingly popular to study animal behaviors with the assistance of video recordings. An automated video processing and behavior analysis system is desired to replace the traditional manual annotation [97–102]. On the other hand, we have being developed an experimental system to study interaction between rats and a mobile robot [103–105]. These experimental results demonstrated that the robot could influence the behaviors of the rats to some degree though, yet the robot could just track the rat and needed to be operated manually in most cases. If the robot could learn and recognize behaviors from visual data of the rat, it will be able to adaptively generate behaviors to interact with rats more actively and autonomously.

However, for conventional animal experiments, behavioral measures are mainly performed visually by trained observers, yielding significant measure errors due to individual differences. In addition, the measurement of animal behaviors is time consuming and not readily compatible with experiments requiring large groups of animals. In an attempt to solve these shortcomings, Kernan et al. [46–48] introduced a computer pattern recognition system to identify the rat behaviors. Nevertheless, the system could not perform in real time, and the accuracy was low because of the methodology and hardware limitations. Hédou et al. [100] presented an automated, accurate and faster method for estimating rat's floating time in the forced swim test. Samuel et al. [101] proposed a computer vision-based automated Figure-8 maze capable of measuring rodent behaviors. However, these two behavioral measures are on particular purpose such as, force swim test and Figure-8 maze test and also should be equipped with high cost apparatuses causing poor feasibility. Thus it is quite necessary to develop a straightforward automated system for general behavioral measure of rats. [102] Proposed a quite effective framework for automatic video based behavior analysis systems for mice, and it achieved high recognition rate of resting, eating, exploring and grooming behaviors. Nevertheless, since the behaviors of the mouse-in-cage scenario were artificially made, it could not accurately and practically represent the real behaviors of animals. Therefore, it is necessary to recognize the behaviors of real animals which will be more likely to be used for the potential actual application. Additionally, wireless inertial sensors have been developed for monitoring small animal behavior as well. As introduced in [106], a small wireless accelerometer that is able to record and measure the activity of rats over time. However, the behavior of rats tends to be easily influenced by the body-worn sensors, so the behavior of rats is not exhibited naturally.

Given the above-mentioned shortcomings, we are aiming to develop a novel video based recognition system for the behavior recognition of real animals by using straightforward image processing and classification methods. The video information perceived by the robot, as well by living creatures, reflects dynamic interactions between the robot and the environment in which the robot is situated [107]. So the recognition system should be able to distinguish the behavior of rats in real-time to guarantee the robot to interact with rats in a natural way, and therefore makes a step towards realistic application. In the behavior-based robotics, motors control signals are generated by the flow of sensor information such as video sequences, which is a function of the robot's own behavior. As stated in Chapter1, the robot is put to-

gether with rats in a square open-field. Surrounded by such a simple environment, the robot is only needed to be controlled to towards the rat. Therefore the behavior planning of the robot is implemented based on the recognized behavior of rats and the aim of experiment.

### 4.1.2 Objective

In this chapter the author proposes a novel methodology to analyze rat behavior by utilizing a general recognition system based on image processing and classification techniques. Additionally, the behavior generation of the robot is achieved based on the behavior analysis of the rat. Thus the purpose of this recognition system involves with two aspects: a) behavior analysis of rats for psychology or pharmacology application b) adaptive behavior generation of the robot to interact with rats. Regarding this two aspects, the most crucial part lies on the recognition of rat behavior. As the interaction between the robot and rats is performed strictly following the rules of psychology and pharmacology, if the recognition system meets the requirements of the interaction experiment between the robot and rats, it suffices to basically analyze the rat behavior for realistic psychology and pharmacology application. As a short-term goal, the author is focusing on the common behaviors of rats that are significantly important for analyzing the results of social interactions, such as moving, rearing, grooming and rotating. Regarding walking or running, it is determined simply just by the speed of the centroid of rat body, so it is not discussed in detail here. The definition of each behavior can be concluded as, **rearing**: rise up on hind limbs; **grooming**: body cuddles and head curls; **rotating**: head and body rotate (Figure 4.1).

In this chapter, to recognize and analyze the behavior of rats, we propose an extremely straightforward method based on the basic image processing algorithm [108]. Likewise, the behavior planning of the robot is dependent on the recognition system.

## 4.2 Features Extraction of Rats based on Image Processing

According to the experiment setup described in [105], just 2D image sequences of rats can be obtained from the CCD camera installed in the top. Firstly, the body shape is the vital information for discriminating rat behavior, and Figure 4.2 shows the involved possible geometric

(a) Rearing



(b) Grooming
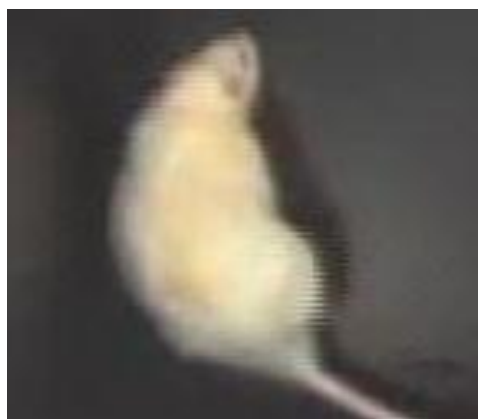


(c) Rotating

Figure 4.1 Typical and vital behavior of the rats in the social interactions with partners
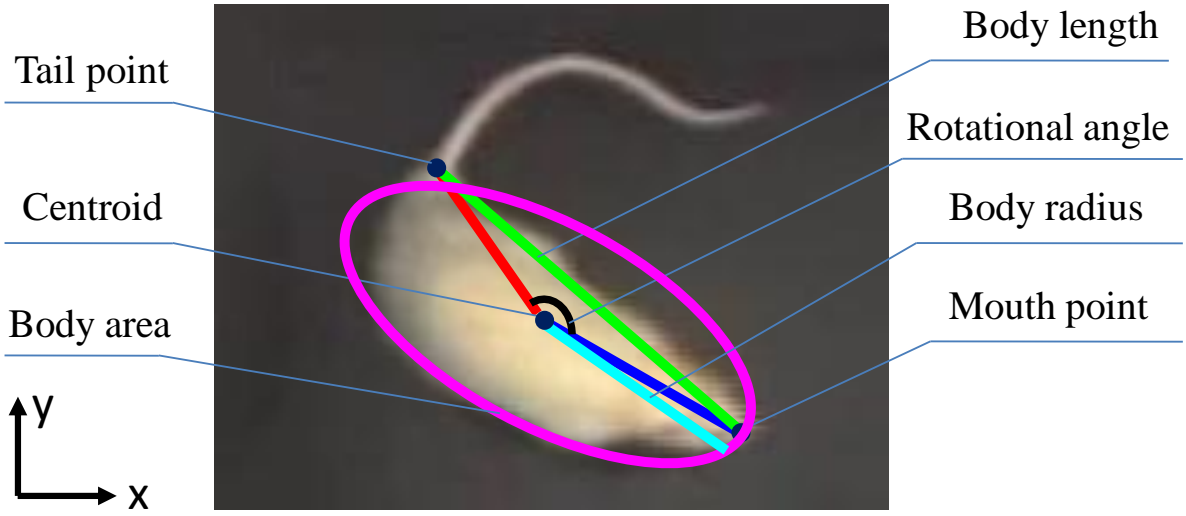
Figure 4.2 Geometric features to represent behaviors of rats. Here the body length, body area, body radius, circularity, rotational angle, ellipticity are extracted to discriminant of rats
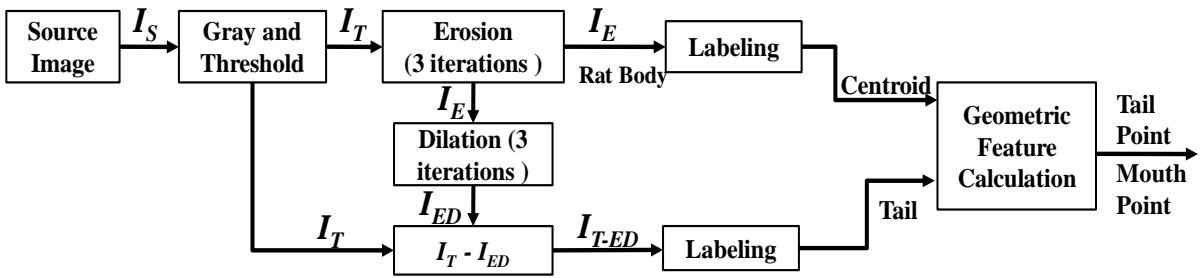


Figure 4.3 Image process to obtain the clue points: mouth point, centroid, tail point. The flowchart contains mainly basic image processing: gray, threshold, erosion, dilation. Extracted clue points greatly contribute to compute other feature parameters

features. Specifically, the body length $L$, body area $S$, the radius $R$ of minimum circumscribed circle of the body without tail part, circularity $E$, rotational angle $\theta$, ellipticity $\rho$ are considered to be the static feature parameters for behavior classification. On the other hand, the dynamic feature can be also significantly important cues. The specific dynamic feature parameters are, locomotion speed of centroid $V_{cx}$, $V_{cy}$, tail point $V_{tpx}$, $V_{tpy}$, mouth point $V_{mpx}$, $V_{mpy}$, and angular speed of rotation $\omega$. So the feature vector of rat behavior is $X = [L, S, R, E, \theta, \rho, V_{cx}, V_{cy}, V_{tpx}, V_{tpy}, V_{mpx}, V_{mpy}, \omega]^T$. The derivation of these parameters will be discussed detailedly in the following subsections.

$$Th(x,y,t) = \begin{cases} 255 & I(x,y,t) > T_b \\ 0 & otherwise \end{cases} \qquad (4.1)$$

### 4.2.1 Clue Points

According to Figure 4.2, the points such as mouth point, centroid, and tail point are significantly important clues to compute feature parameters. The centroid, tail point, mouth point of the rat is extracted based on the initial image process as shown in **Error! Reference source ot found.**. Given input gray image sequence $I(x,y,t)$, the threshold image sequence $Th(x,y,t)$ can be calculated based on the threshold gray value $T_b$ as described in Eq.4.1. After implementing erosion to eliminate noise and tail, the body image $I_E$ (white region) of the rat without tail is obtained.

As mentioned in [105], the experimental white rats are put in the open-field with an absolutely black background. However, extracted white part of the image may be composed of several separate regions due to few white flaws caused by light illumination. In general, the largest region is considered to be the rat obviously. Here we employ the labeling algorithm [109] to extract the largest region as shown in **Error! Reference source not found.**. After xtracting the rat body, given the coordinates of all pixels, the centroid of the rat body can be computed as the following equations.

$$(c_x(t), c_y(t)) = (\frac{M_x(t)}{S(t)}, \frac{M_y(t)}{S(t)}) \qquad (4.2)$$

$$S(t) = \sum_{x,y} D(x,y,.t) \qquad (4.3)$$

$$M_x(t) = \sum_{x,y} xD(x,y,t) \quad M_y(t) = \sum_{x,y} yD(x,y,t) \qquad (4.4)$$

Note that $(c_x(t), c_y(t))$ is the coordinate of centroid, $D(x, y, t)$ the coordinate of body image $I_E$, $S(t)$ the area of rat body in number of pixels.

To extract the tail of the rat, as shown in **Error! Reference source not found.**, at first we btain image $I_{T-ED}$ by subtracting the pixels of image $I_{ED}$ from $I_T$. After implementing labeling processing on $I_{T-ED}$, a very clear tail is available, and the contour $t(x, y, t)$ around the tail is

extracted. We assume the tail point $(tp_x(t), tp_y(t))$ in the contour $t(x, y, t)$ is determined by calculating the minimum distance between the tail and centroid. Thus $(tp_x(t), tp_y(t))$ is also just the connection point of body and tail. Consequently, the point located in the contour $b(x, y, t)$ around the body has the maximum distance with the tail point is thought to be the mouth point $(mp_x(t), mp_y(t))$. These two points is determined by the following two equations respectively. $f$ is the function to calculate the distance between a contour and a point.

$$(tp_x(t), tp_y(t)) = \arg\min_{x,y} f(t(x, y, t), (c_x(t), c_y(t))) \tag{4.5}$$

$$(mp_x(t), mp_y(t)) = \arg\max_{x,y} f(b(x, y, t), (tp_x(t), tp_y(t))) \tag{4.6}$$

## 4.2.2 Calculation of Feature Parameters

Given Eq.4.2, Eq.4.5 and Eq.4.6, the speed of centroid, tail point and mouth point can be computed by the following equations respectively.

$$V_{cx} = \frac{\partial c_x(t)}{\partial t} \qquad V_{cy} = \frac{\partial c_y(t)}{\partial t} \tag{4.7}$$

$$V_{tpx}(t) = \frac{\partial tp_x(t)}{\partial t} \qquad V_{tpy}(t) = \frac{\partial tp_y(t)}{\partial t} \tag{4.5}$$

$$V_{mpx}(t) = \frac{\partial mp_x(t)}{\partial t} \qquad V_{mpy}(t) = \frac{\partial mp_y(t)}{\partial t} \tag{4.6}$$

As described in Eq.4.3, the body area $S$ is determined simply by summing all the pixels of the body region. In this subsection, other feature parameters body length $L$, body radius $R$, circularity $E$ and rotational angle $\theta$ will be calculated. Firstly, body length $L$ and body radius $R$ are determined by the following equations.

$$L(t) = \sqrt{(tp_x(t) - mp_x(t))^2 + (tp_y(t) - mp_y(t))^2} \qquad (4.7)$$

$$R(t) = \underset{x,y}{\arg\max}\, f(c(x, y, t), (c_x(t), c_y(t))) \qquad (4.8)$$

$$E(t) = \frac{S(t)}{\pi R(t)^2} \qquad (4.9)$$

When supposing the centroid, tail point and mouth point as the vertices of a triangle, rotational angle $\theta$ (an internal angle of the triangle formed by the three clue points) can be calcu-

$$sd_{0,1}(t) = \sqrt{(c_x(t) - mp_x(t))^2 + (c_y(t) - mp_y(t))^2} \qquad (4.10)$$

$$sd_{0,2}(t) = \sqrt{(c_x(t) - tp_x(t))^2 + (c_y(t) - tp_y(t))^2} \qquad (4.11)$$

$$sd_{1,2}(t) = \sqrt{(mp_x(t) - tp_x(t))^2 + (mp_y(t) - tp_y(t))^2} \qquad (4.12)$$

$$\theta(t) = \arccos\left(\frac{sd_{0,1}^2(t) + sd_{0,2}^2(t) - sd_{1,2}^2(t)}{2sd_{0,1}(t)sd_{0,2}(t)}\right) \quad \omega(t) = \frac{\partial\theta(t)}{\partial t} \qquad (4.13)$$

lated. The angular speed of rotation $\omega$ is obtained by differentiating $\theta$ with respect to time.

Generally speaking, the body of rats appears mainly long and narrow when exhibiting behaviors. Accordingly, we fit the appearance of the body as ellipse following the steps of Figure 4.4. Body image $I_E$ is obtained by implementing gray, threshold and erosion operation to the source image $I_S$. The contour around body is extracted by implementing Contour Finding method referenced from extremely robust and popular OpenCV library [110]. Based on the extracted contour, we can fit appropriate ellipse to the rat's body. According to the long and short axis $(e_a(t), e_b(t))$ of the fitted ellipse, the ellipticity $\rho$ is derived as the following equation.

$$\rho(t) = \frac{e_a(t)}{e_b(t)} \qquad (4.14)$$
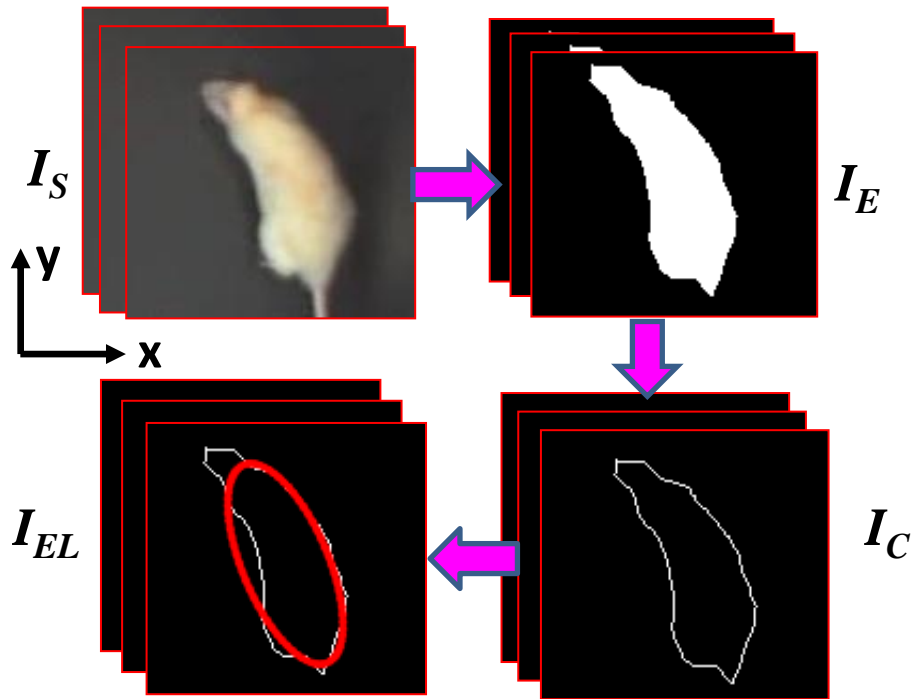
Figure 4.4 Fit ellipse to the shape of rat's body. $I_S \rightarrow I_E$ is exactly the same processing step of $I_S \rightarrow I_T \rightarrow I_E$ as shown in Fig.2. Find contours and fit ellipse employ the algorithm referenced from the OpenCV library
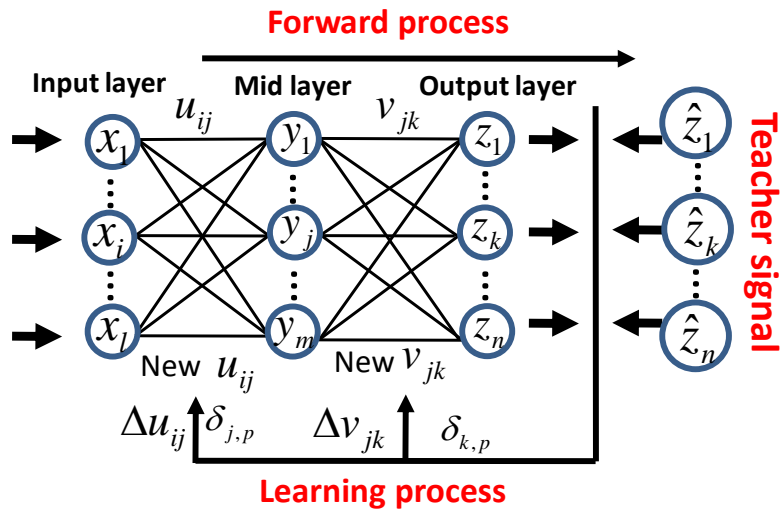


Figure 4.5 Back propagation algorithm for training 3 layers neural networks. The training process is to update the weights $u_{ij}$, $v_{jk}$, to decrease the errors between output $z_k$ and teacher signal $\hat{z}_k$

# 4.3 Behavior Recognition of Rats by Using SVM and ANN

## 4.3.1 Classification Methods

After calculating the feature parameters, we perform behavior classification. We have used quite powerful and straightforward classification methods ANN (Artificial Neural Network) [111–113] and SVM (Support Vector machine) [69, 70] algorithm to classify the behaviors of the rats.

The ANN is trained with the back-propagation algorithm (supervised learning concept). Here three-layer neural network are used to train all the input feature vectors (Figure 4.5). The operation of this network can be regarded as the following formula.

$$z_k = f_o[\sum_{j=1}^{m} v_{jk} f_{mi}(\sum_{i=1}^{l} u_{ij} x_i)] \tag{4.15}$$

Where $x_i$ denotes the input feature vector, $z_k$ the output value, $u_{ij}$ the weight between input node $i$ to mid node $j$, $v_{jk}$ the weight between Mid node $j$ to Output node $k$, $f_o$, $f_{mi}$ the transfer function used at Output layer and Mid layer nodes, respectively. Here, we used the following sigmoid function the activation function in the Mid and Output layers.
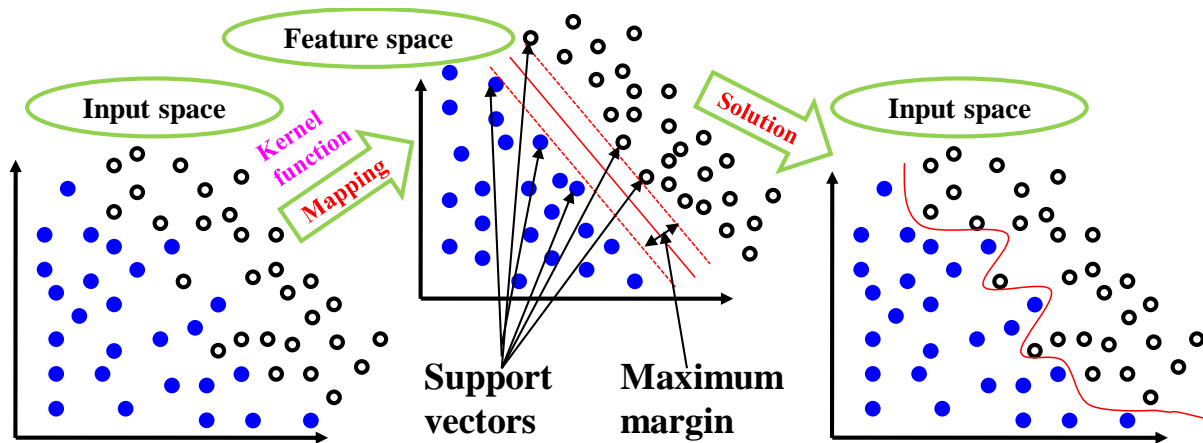


Figure 4.6 Overview of the Support Vector Machine process. Transform input vectors into a higher dimensional space to make it possible to perform the separation. As in general, separa-

tion becomes easier in higher dimension

$$g(x) = (1 + e^{-x})^{-1} \qquad (4.16)$$

An SVM (Support Vector Machine) performs classification by constructing an N-dimensional hyperplane that optimally separates the input vectors into two categories. To make the separation easier to perform, the concept of kernel function is introduced to make the input vectors into a higher dimensional space (Figure 4.6). In this way, a linear separation in the new space becomes equivalent to a non-linear classification in the original space. According to the advantages narrated in LIBSVM [116]. In this study, we create a nonlinear classifier by using the following RBF (Radial Basis Function) kernel.

$$k(x, x_i) = e^{-\gamma |x - x_i|^2} \qquad (4.177)$$

Besides, another parameter is C (the penalty parameter of the error term). [117] Gives an effective method about how to determine the best parameter C and $\gamma$, here 2 and 0.07 are chosen to train feature dataset of rat behavior.

### 4.3.2 Dataset and Classification

*A. Experimental Setup*

The experimental apparatus we are using is shown in Figure 4.7. The rat and robot are put into a $700 \times 700$ mm open-filed for interaction experiments. The positions and behaviors of the rat and robot can be detected by a CCD camera (pixel: $640(H) \times 480(V)$) affixed on the top of the enclosure chamber. At first, the video stream is preprocessed by a video capture board embedded into a high-performance computer, and it is processed online based on our recognition system; simultaneously the video stream is recorded as video file for more detailed offline-analysis. The real-time recognition results make the robot capable of knowing where the rat is and what it is exhibiting. Thus the robot can do corresponding actions to the rat, e.g. imitation. Consequently, the experiments can be performed in the enclosure and operant chamber autonomously without human intervention. As the position of the rat and robot can be measured in our previous system [103], we focus on the recognition of rat behaviors in current research.
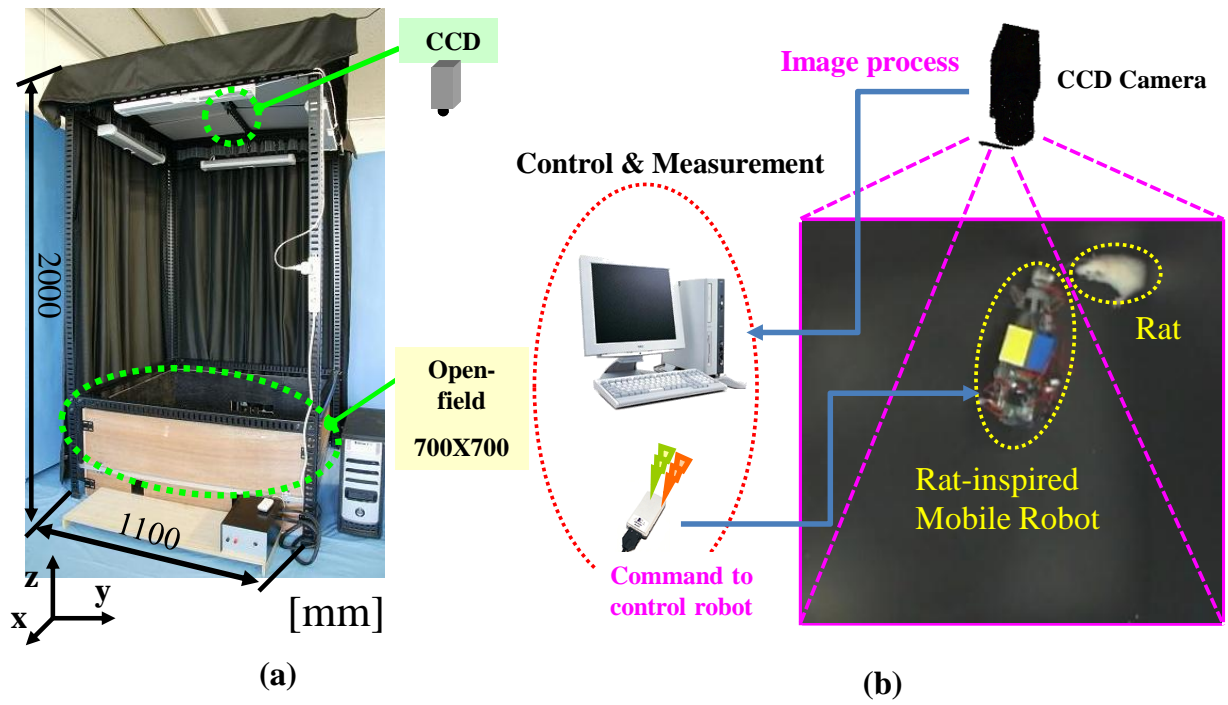
Figure 4.7 Experimental system: (a) side view of the enclosure and operant chamber including the open-field, CCD camera and computer; (b) top view of the control and measurement system for interaction experiment between the robot and a rat

### B. Dataset

We have evaluated this recognition system using video streams captured by the CCD camera depicted in Figure 4.7. Video sequences in approximately 30 f/s of 3 male F344/Jcl rats aged 8 weeks were recorded respectively with the solution of $640 \times 480$ pixels and duration of 10 minutes. The number of total frames is $10 \times 60 \times 30 \times 3 = 54000$. We extract each feature vector in a 3-frame segment, so the number of total feature vector patterns is $54000 \div 3 = 18000$. As the frame rate is 30 f/s, so in every 3 frame, the behavior of rats is quite likely to be invariable. Moreover, given a feature vector $x_i$, we use mean filter as shown in the following equation to compute arithmetic mean of $x_i$ and its neighbor vector $x_{i-1}$ and $x_{i+1}$ as the final values.

$$x_i = \frac{1}{3}(x_{i-1} + x_i + x_{i+1}) \tag{4.18}$$

The mean filter decreases errors caused by measurement noises and improve the data reliability as well. As ANN and SVM are supervisor learning algorithms, the ground truth $\hat{z}$ is required. We have obtained ground truth by integrating all the observation results of 3 trained observers. However, unfortunately, even in the same frame the measured results of different observers may be different. In this case we selected the result with dominating support of the 3 observers as the final ground truth.

All the behavior representative feature parameters are packaged as the input space data of ANN and SVM. However, their magnitudes vary extremely between each other. For instance, $L$ usually ranges with thousands of magnitude while $\rho$ is generally no more than 10, causing $L$ dominating significantly. Furthermore, it will increase numerical difficulties during the calculation. Thereby it is quite necessary to scale all the input feature parameter data in the same magnitude. As an example illustrated in Figure 4.8, for the recognition of rearing based on ANN without data scaling, the recognition rate is just keeping on 20% during all the training process. Comparatively, the recognition rate increases gradually and has risen more than 80%
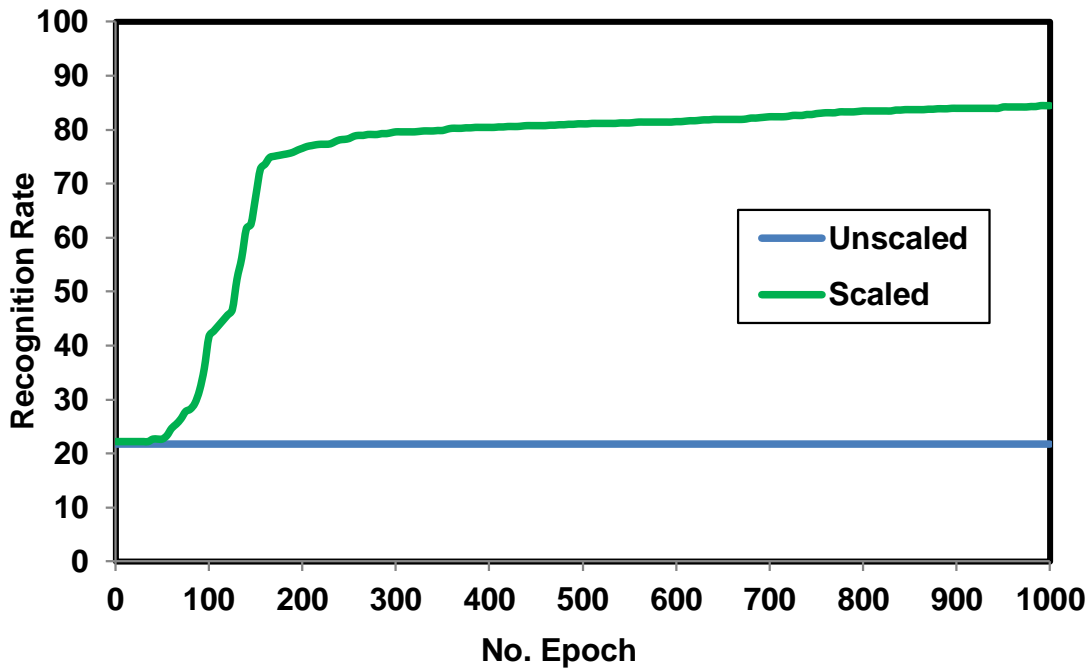


Figure 4.8 The recognition rate of rearing with data scaling and without data scaling based on the ANN training system. Regarding the recognition rate in the unscaled data, there is no shrinkage during all the training process that means failure recognition.

finally when the data is scaled. Magnitude differences between feature parameters make the training process terminate. Therefore for all the data, we linearly scale every feature parameter to the interval [0, 1].

### C. Data Training

According to [118], P-fold cross-validation technique has superior performance than RSS (repeated random subsampling) and L1O (leave-one-out). Thus P-fold is employed as the training and validation phases of ANN and SVM. In P-fold cross-validation, for each behavior, the 18000 feature vectors are divided into P = 10 partitions, where the 1800 feature vectors in each partition are selected completely randomly. One of the P partitions is retained as the validation dataset and the remaining P − 1 partitions are used for training. The P results from the folds are then averaged to produce a single estimation. The random partitioning is repeated 10 times to guarantee all the partitions can be validated, and the average correct differentiation percentage is reported.

Regarding ANN, for each pattern of training set, if the trained result is equal to the ground truth, the number of correct results will increase. When the entire training set is covered, an epoch is completed. The errors between the desired and actual outputs are computed at the end of each epoch and these errors are averaged. The training process is terminated when specified maximum number of epochs (1000) is exceeded or error rate is less than 1%. The training rate can be obtained by calculating the ration between the number of correct trained results and total trained patterns. During training process, the trained weights $u_{ij}$, $v_{jk}$ were updated to decease the errors according to the back propagation algorithm. Furthermore, the latest updated weights were used to evaluate the validation patterns. Similarly the validation rate is obtained by calculating the ratio between the number of correct validated results and total validation patterns. When considering SVM, the author use the best parameter C(2) and γ(0.07) of the RBF kernel function described in section 4.3.1 to model the dataset. Based on this model, the training and testing recognition rates are calculated respectively.

### D. Results

Table 4.1 illustrates the total results. Each recognition rate is averaged with the results of 5 runs. All the recognition rates of testing data are quite near that of training data, which ac-

counts for the effectiveness of ANN and SVM. In general, recognition rates of all the behaviors are over 80%, revealing the robustness of our recognition system. In addition, the recognition rates of SVM are higher than that of ANN as a whole (Rearing: ~12%; Grooming: ~2%; Rotating: ~3%;). That is partly because the SVM can find the optimal classification hyperplane by support vectors based on the RBF kernel function while the ANN is based on the sigmoid function. The confusion matrix for the validation set is shown in

Table 4.2. The values in the table are obtained by adding the classified results of all the partitioned validation sets (totally 10 partitions). The rearing behavior tends to be misclassified as the rotating behavior in the case of both SVM and ANN, and vice versa. In addition, the rearing behavior sometimes is incorrectly classified as grooming behavior as well. The main reason is that the motion parameters extracted to discriminate these behaviors are still limited. Figure 4.9 illustrates clearer behavior recognition results of one validation set. As mentioned before, 1 segment actually has the interval of 3 frames. Figure 4.10 compares the computational costs of classification training process with respect to SVM and ANN respectively. The

Table 4.1 Results of behavior classification

| | Recognition rate (%) | | | |
| | SVM | | ANN | |
| Behavior | Training set | Validation set | Training set | Validation set |
| --- | --- | --- | --- | --- |
| Rearing | 94.0±0.15 | 93.06±0.11 | 84.5±0.27 | 81.2±0.29 |
| Grooming | 99.8±0.02 | 98.3±0.03 | 99.0±0.04 | 96.6±0.09 |
| Rotating | 97.1±0.10 | 94.2±0.16 | 94.5±0.17 | 91.6±0.23 |

Table 4.2 Confusion matrix for the validation set

| | SVM | | | ANN | | |
| | Rearing | Grooming | Rotating | Rearing | Grooming | Rotating |
| --- | --- | --- | --- | --- | --- | --- |
| Rearing | 94 | 1 | 3 | 82 | 1 | 4 |
| Grooming | 1 | 58 | 1 | 4 | 57 | 2 |
| Rotating | 5 | 0 | 145 | 7 | 0 | 141 |
| Others | 1 | 0 | 5 | 8 | 1 | 7 |
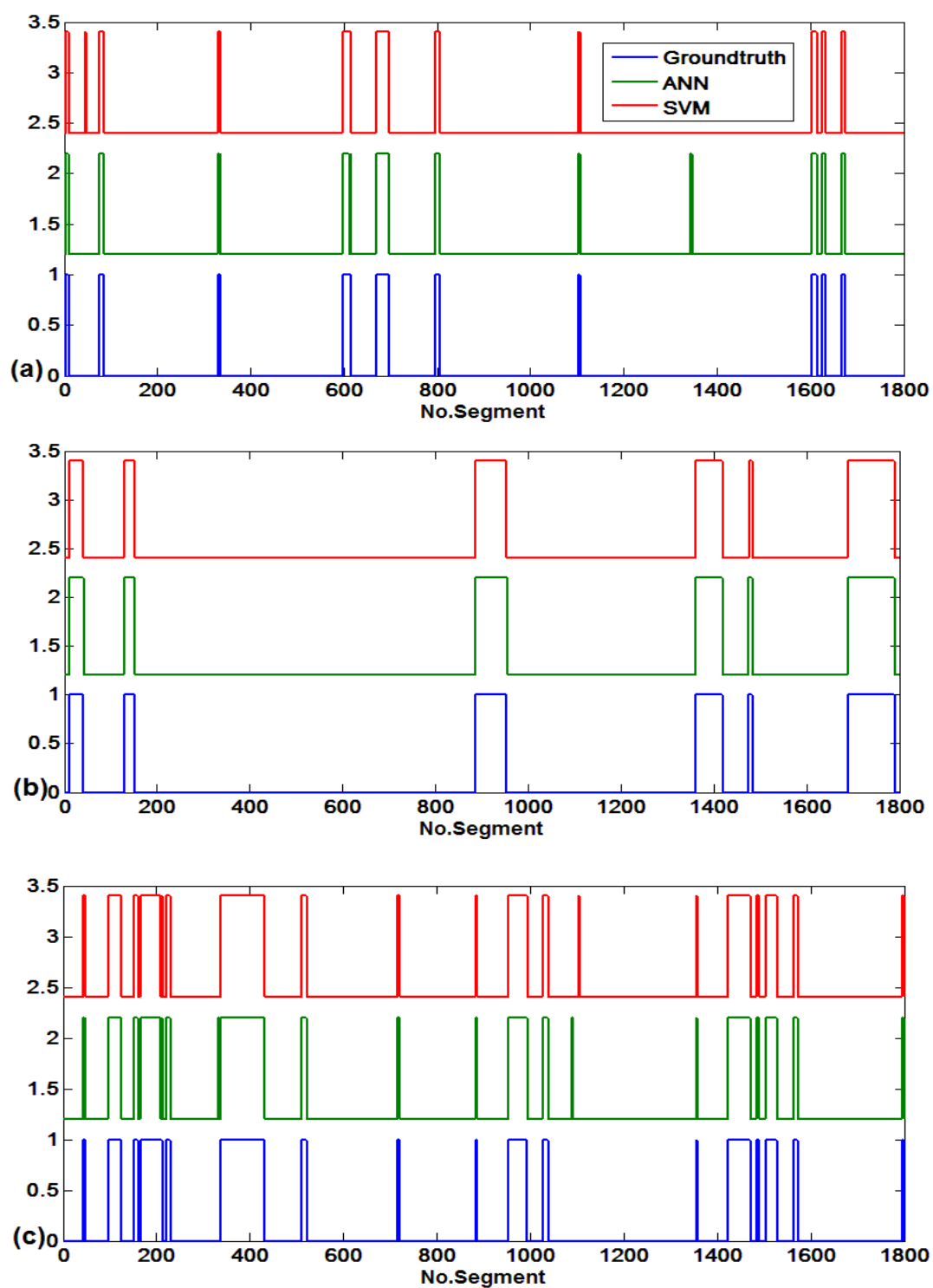
Figure 4.9 Classification results of one validation set in the case of ANN, SVM and Ground-truth. (a)Rearing (b)Grooming (c)Rotating for each row the high value represents rearing or grooming or rotating, while low value represents non-rearing or non-grooming or non-grooming.
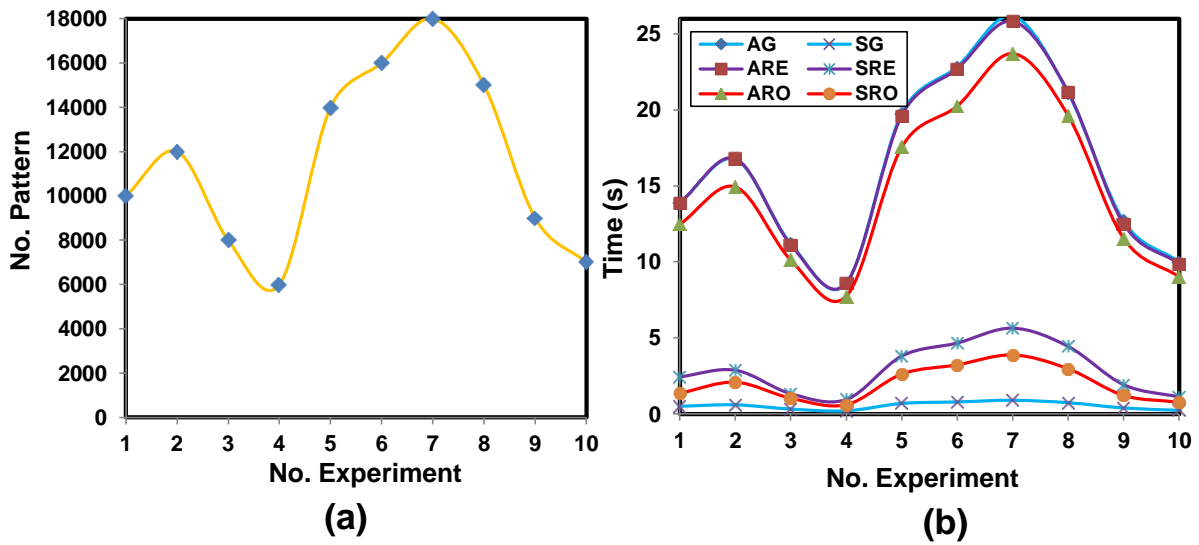
Figure 4.10 Training time f behavior recognition based on the ANN and SVM. Each result is calculated over 3 runs. (a)Experiments and the number of corresponding patterns; (b)the mean training time of each behavior recognition based on SVM and ANN; SRE: SVM for rearing; SG: SVM for grooming; SRO: SVM for rotating; ARE: ANN for rearing; AG: ANN for grooming; ARO: ANN for rotating

mean time consumption is calculated with visual studio 2008. The system is on the basis of common PC framework, using Intel Core 2 Duo 3.16G CPU, 2G RAM. Computational time of SVM is approximately about 5 times less than that of ANN, showing the superior performance of SVM.

SVM performs better than ANN in not only the recognition rate but also the computational cost, thus the author employed SVM as the preferable classification technique in. The SVM-based recognition system is accurate enough to replace the traditional manual annotation. Likewise, it meets the demand of measuring the indices involved with evaluating sociality and anxiety in the social interaction test.

Based on the recognition system, the author made an interface to monitor and analyze the behavior of rats (Figure 4.11). The motion parameters consist of static parameters and dynamic parameters of rats are shown in the interface, allowing real-time analysis of rat behavior. The rearing, grooming and rotating are recognized by SVM, while the walking and running are recognized in the light of the centroid speed. The frequency and duration of each behavior are recorded and saved. Simultaneously, all the motion parameters are recorded and saved as
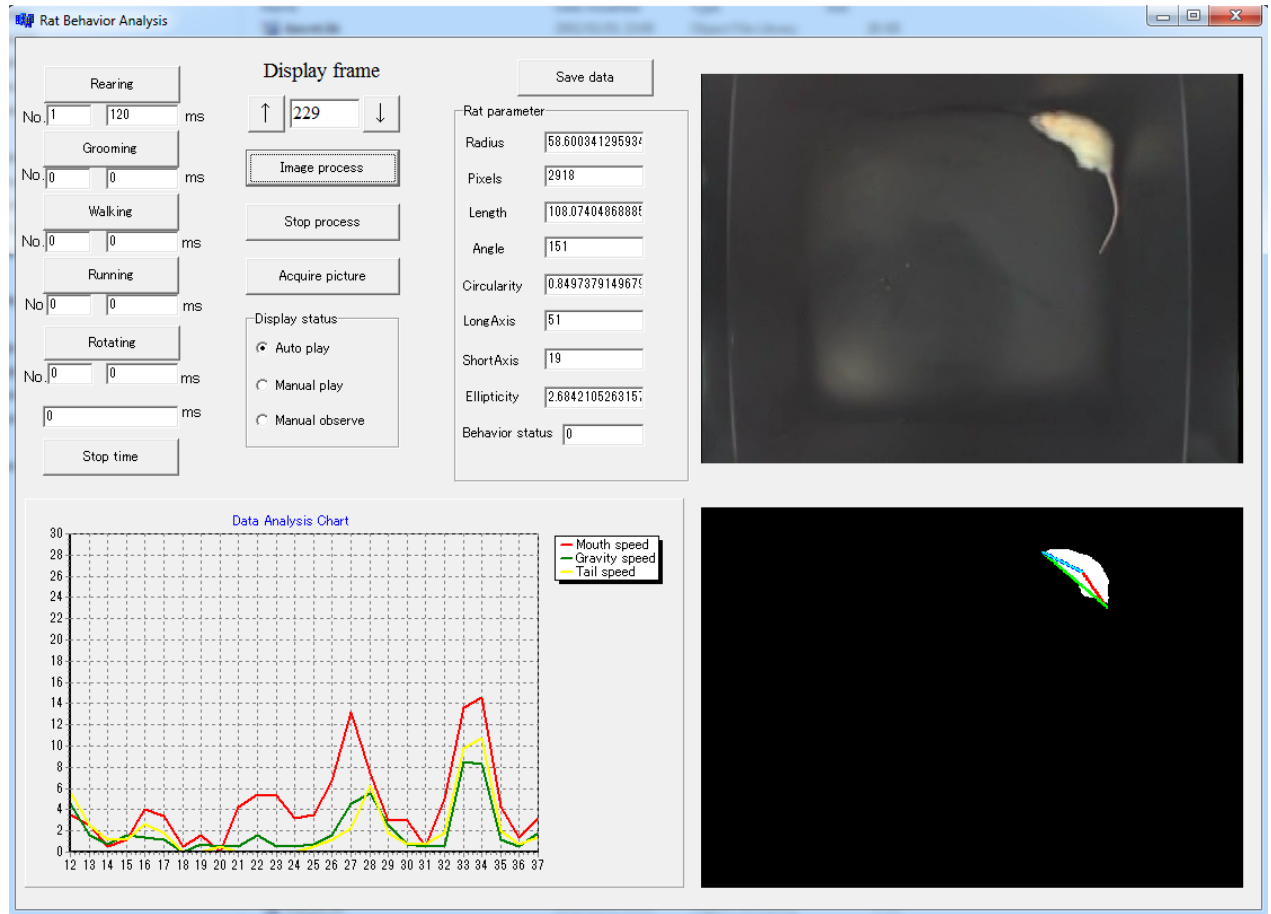
Figure 4.11 The interface for the behavior analysis of rats

well. Therefore, it is convenient to review history records of all the data, allowing more de-tailed off-line analysis of rat behavior.

## 4.4  Behavior Planning of the Robot

As shown in Figure 4.12, the behavior of the robot is generated based on the recognized rat behavior $f_b^2$ and current motion status of the robot $X_2$. As described in Chapter 2, the motion parameter $X_2$ consists of motion parameters of robot $X_2^{robot}$ (e.g., $v$, $\theta$), rat $X_2^{rat}$ (e.g., $v$, $\theta$) and the motion relationship $X_2^{r\text{-}r}$ (e.g., the distance between robot and rat $d$). $X_2^{rat}$ varies individu-ally, as well as with experimental conditions. Therefore, the robot is able to generate behavior $f_b^3$ adaptive to the environmental conditions and individual differences in rats.

The robot roughly can generate three types of behavior: friendly, agonistic, neutral. How-ever, for a specific action, it is difficult to distinctly understand which one of the three types it
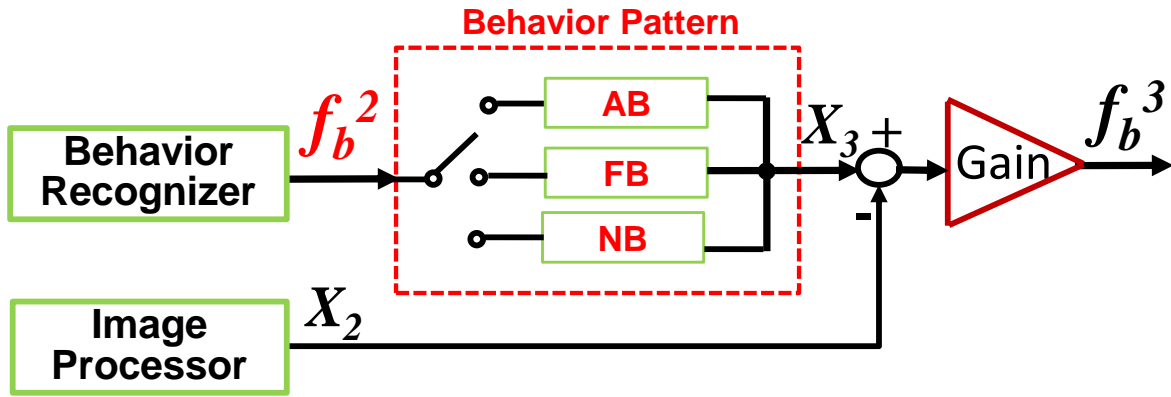
Figure 4.12 Behavior generation of the robot based on the recognized rat behavior ($f_b^2$) and current motion status of the robot and rat ( $X_2$)

belongs to. For instance, when the rat is running, the robot will move in a high speed to follow the rat, in this case, the behavior of robot is considered as neutral behavior. When the rat is move very slow or stays still, the robot chases it in a high speed, will be probably considered as agonistic behavior.

In general, the robot will generate corresponding behaviors to meet the experimental purpose. In case of creating RMMD, the robot will give stress to rats by generating agonistic behaviors. To create friendly relationship with rats, the robot will generate friendly behavior to interact with rats. Likewise, the friendly interaction is considered to be able to decrease the stress level of rats. Neutral behavior generally will be generated to interact with the rats as evaluation or comparison. As the differences in the results of rats exposed to agonistic and neutral (or friendly and neutral) robot, can be analyzed to find the effects of agonistic or friendly robot-rat interaction.

As shown in Figure 4.13, the author is focusing on mainly the typical behaviors of rats, such as rearing, grooming and moving. Regarding the friendly behavior, the robot imitates what the rat is acting. To generate agonistic behavior, the robot is continuously chasing the rat in a high speed to induce stress. When interacting neutrally to the rat, the robot does nothing but keeps on following the rat softly.

Based on the recognition system, the robot can definitely understand the behavior and position of rat. Furthermore, the speed and position of the robot can be obtained as well.
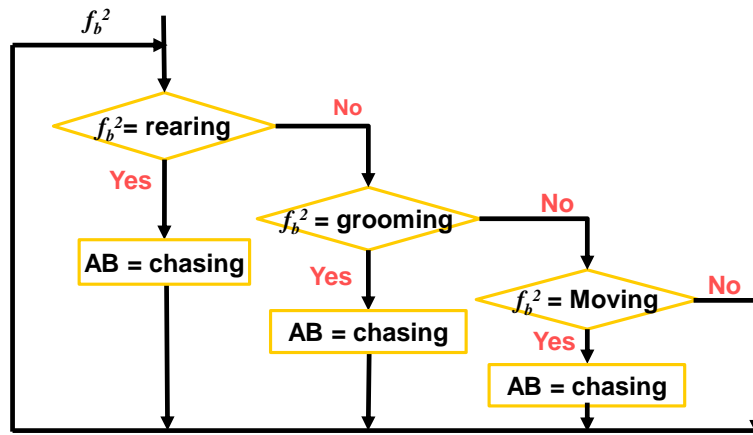
(a) Agonistic behavior generation
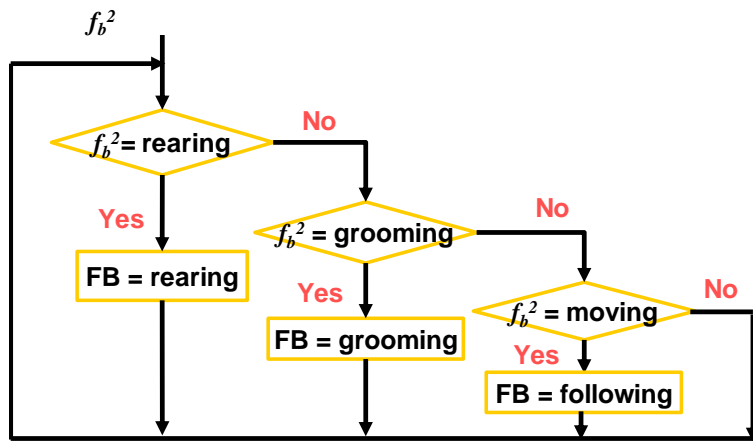


(b) Friendly behavior generation
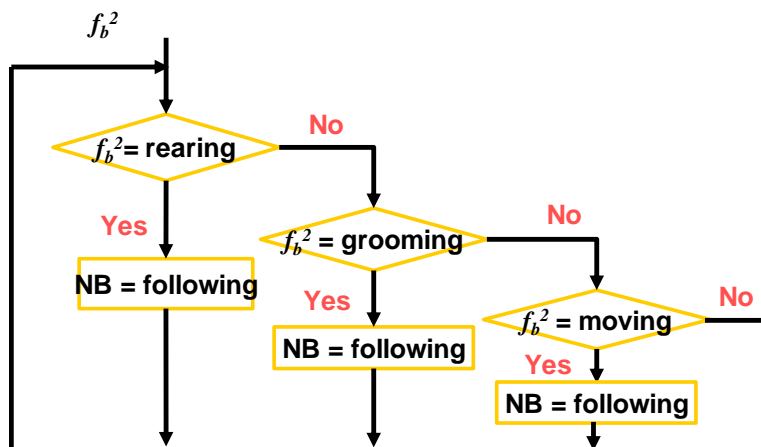


(c) Neutral behavior generation

Figure 4.13 The behavior generation of robot corresponding to the frequently exhibited rat behavior
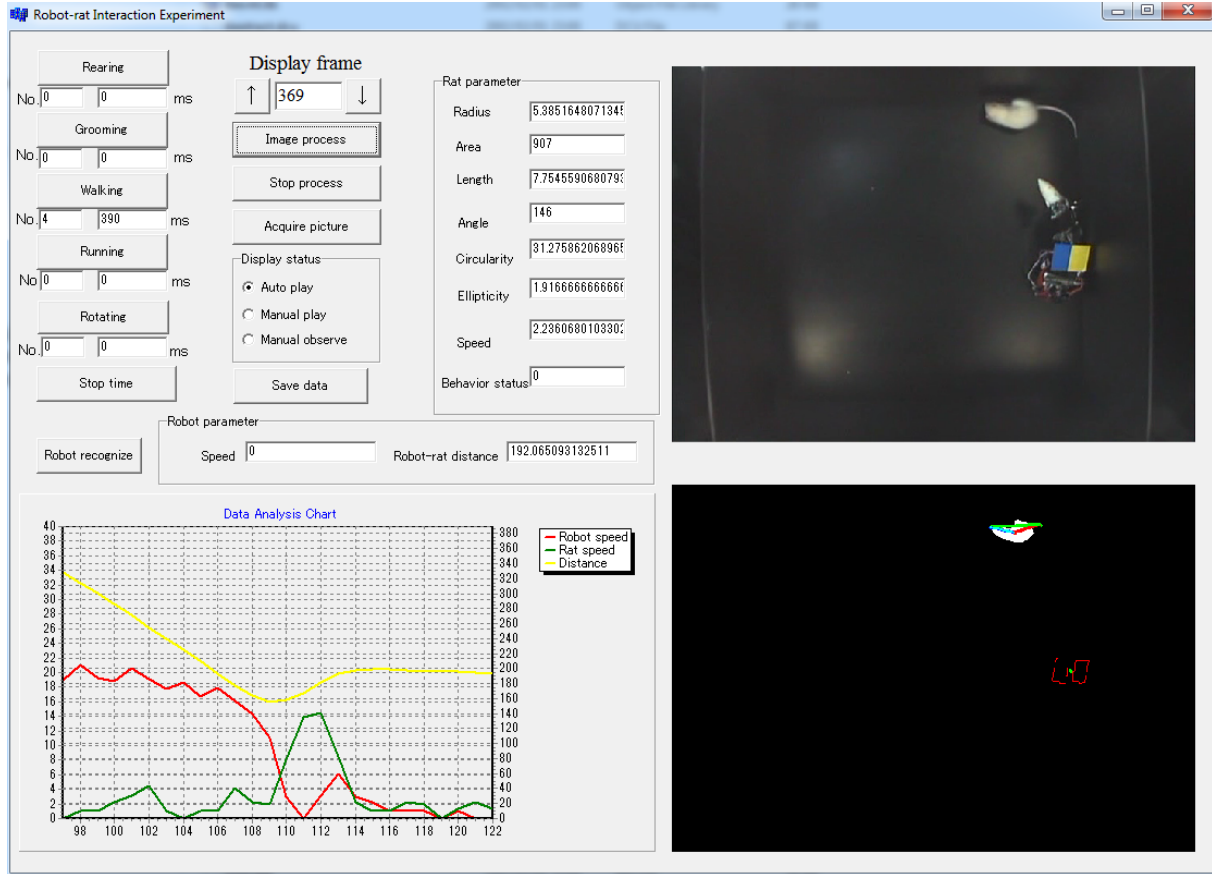
Figure 4.14 Control interface to monitor the behavior of robot

Consequently, robot can be adjusted to the target behavior and position by operating the interface as shown in Figure 4.14.

# 4.5  Discussion

### 4.5.1 Behavior Recognition of Rats

The recognition system by using both SVM and ANN are tested to be able to classify the rearing, grooming, and rotating behaviors of rats with rates of more than 80%. It is sufficiently precise to analyze the rat behavior during the interaction with a robot. As SVM provides better recognition rate and lower computational cost, the author selected SVM as the classifier to build the recognition system. Consequently, a SVM based recognition system that achieves not only less computational load but also higher recognition rate has been developed. Fur-

thermore, as we just need to extract the geometric features and dynamic motion parameters of the rat based on basic image processing, our system is considered to be quite straightforward.

Certainly there are still some potential defects in current recognition system. For instance, the classification confusion between rearing and rotating behaviors seems a little high, due to insufficient feature parameters. More feature parameters should be extracted to represent behavior attributes correctly. Adding other sensors may be an effective potential solution to this bottleneck. In addition, currently the background of experimental apparatus is quite unitary (just back), making it is easy to extract the body part of the rat. Robust recognition system could extract the object even in the case of complex background. In addition, the feature vector for different behavior should be selected before training to get more accurate results. However, the SVM based recognition system is enough for behavior recognition of real rats due to its superior performance.

### 4.5.2 Behavior Planning of the Robot

Behavior planning of the robot is achieved based on recognized rat behavior. Three types of behavior: agonistic, friendly, neutral behaviors can be generated correspondingly to interact with rats. The robot attack rats and acts as stressor when exhibiting agonistic. This kind of interaction can be used to create RMMD. On the contrary, the friendly interaction is resulted from the imitation of rat behavior by the robot. The neutral interaction in general is implemented to compare with other two types of interaction.

However, the generated behaviors of the robot are restricted due to the limited hardware. As discussed in Chapter 3, for the future work, the robot should be able to generate more various behaviors to imitate realistic interaction as real rats. However, in the view of developing novel platform with real animals, currently the generated behaviors of the robot are enough to reproduce substantial interaction with real rats.

# 4.6  Summary of this Chapter

This chapter proposed an automated video processing and behavior analysis system to replace the traditional manual annotation, and improve adaptivity of the robot to interact with rats.

The main contribution of this recognition system lies on the real-time classification of rat behaviors and adaptive behavior planning of the robot.

1) Based on the selection criteria in generality and importance of rat behaviors, the rearing, grooming, and rotating behaviors were specially focused. Basic image processing algorithm as Labeling and Contour Finding are employed to extract feature parameters (body length, body area, body radius, circularity, rotational angle, and ellipticity) of rat behaviors. Based on these static parameters, the dynamic feature parameters such as locomotion speed of centroid, tail point, mouth point, and angular speed of rotation can be obtained. These parameters are integrated as the input feature vector of ANN and SVM classification methods respectively. Preliminary experiments reveal that the behaviors rearing, grooming and rotating could be recognized with extremely high rate (more than 90% by SVM and more than 80% by ANN). Furthermore, SVM needs less training computational cost than ANN. Therefore, SVM is superior to ANN for the behavior recognition of rats.

2) Based on the recognition system, the robot is able to generate agonistic, friendly, neutral behaviors correspondingly to interact with rats. So the behavior of the robot can be generated to be adaptive to the behavior of rats. But the behavior planning of the robot is still improvable to enable more various interactions.

# Chapter 5

# Development of Rat Models of Mental Disorder

## 5.1 Introduction

### 5.1.1 Background

Recently, the number of patients with mental disorders is increasing in advanced countries such as Japan, USA or European countries. For instance, the number of the patients with mood disorders such as depression doubled in the recent decade in Japan [7]. Therefore, many studies have been performed to develop effective treatments for mental disorders not only in clinical medicine but also in basic medicine. These studies have been playing a very important role for clarifying mechanisms of mental disorders and developing new psychotropic drugs. To effectively screen psychotropic drugs, several researchers have been attempting to develop RMMD [2–4]. In particular, Griebel and Louis have found out that Saredutant (SR48968) has anxiolytic-like and antidepressant-like effects [119–121].

In clinical medicine, the stress-vulnerability hypothesis is now well recognized as one of the most suitable ideas to explain how mental disorders occur in humans [68], [69]. There are few doubts that the stress from environment greatly prompt to induce the mental disorder on patients. In this hypothesis, there are individual differences in stress vulnerability, and the mental disorder occurs in the patient when the severe stress exerts on his or her vulnerability.

Environment → Rat → Abnormal Behavior

Robot — Stress
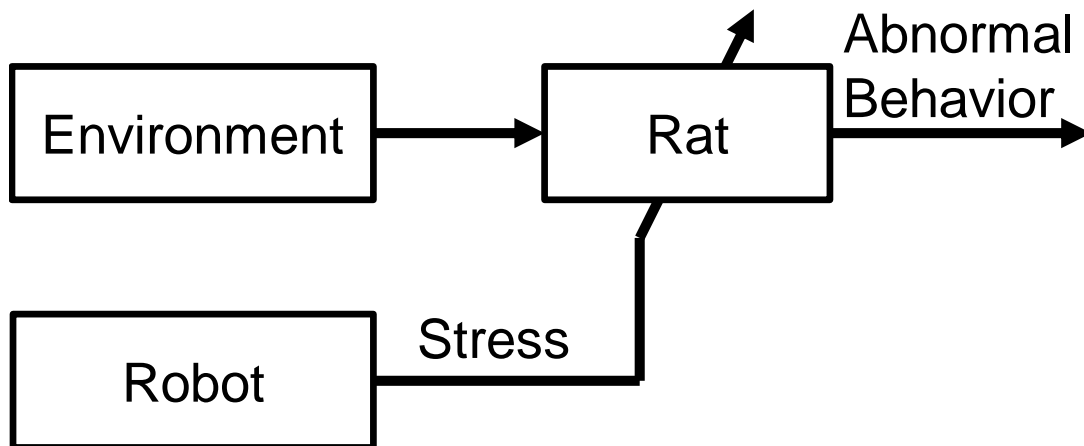
Figure 5.1 Basic concept to create RMMD

When two people are induced a stress together, it might happen that the mental disorder occurs in one while it doesn't in the other. It can be explained using the stress vulnerability hypothesis.

RMMD greatly contributes to developing psychotropic drugs. Studies on the vulnerability have been well done in genetics, biochemistry and neuroscience though, how the stress acts on occurrence of mental disorders still is not clear. The stress induced from the environment should be more considered to make more suitable RMMD. However, there have not been useful experimental methodology and setups to induce and control the stress from the environment.

On the other hand, the author has been developing an experimental system to study interaction between a rat and a small mobile robot [88], [91], [95]. Given this novel experimental system, the author aims to establish methodology to create more suitable RMMD. As shown in Figure 5.1, stress can be induced in the rats when the robot exhibiting stressful behaviors during interaction. When the stress of the rat increases to some extent, some changes might occur in its neural circuit or biochemical system, and it becomes to behave like patients with mental disorders, i.e., RMMD.

A person who experienced much stress, such as violence or lack of affection during childhood, has a higher risk to suffer from mental disorders after growing up [122], [123]. Accordingly, to create RMMD, the robot exhibits stressful/neutral behaviors to juvenile rats in the experiments. The validity and reliability of these rats are evaluated when the rats become

adult to confirm the effect of stress exposure. In these tests, the rats exposed to WR-3 acting stressfully in immature period expressed less activity like the patient with depression than the rats exposed to WR-3 acting neutrally. These findings suggest that the small mobile robot can be used to create effective RMMD.

As described high stress level is assumed as one of the main environmental factors to induce mental disorder, but the problem is how to represent the stress level of rats. This research focuses on the animal behavior, so mainly the parameters involved behavior, e.g., activity and frequency of exhibiting typical behaviors ($a_m$, $f_r$, $f_g$, $d_{rb-r}$), are considered. So these parameters will be scored during the stress exposure experiments for analysis.

### 5.1.2 Objective

The objective of this chapter is detailed below which covers two aspects.

- To create RMMD based on the stress exposure experiments with robots. As described in [67], the vulnerability of rats can be induced when attacked by a robot during immature period. According to the stress-vulnerability hypothesis, the rats with vulnerability may suffer from mental disorder when receiving external stress.

- To determine the coefficients of Eq.2.1 introduced in Chapter 2 by analyzing the stress of rats induced by the robot. These coefficients indicate how each index contributes to the stress level of rats. So how each index affects the stress level of rats can be obtained as well.

## 5.2  Stress Exposure Experiments and Analysis

### 5.2.1 Experiment Setup

The rats and WR-3 are put into a 700×700 mm open-field [25] to conduct experiments. As shown in Figure 5.2, the positions and behaviors of the rat and robot can be detected by a CCD camera (solution: 640×480 pixels) affixed on the top of the open-field. Especially the motion parameters and behaviors of rats can be classified and analyzed by the recognition system proposed in [108]. Receiving the commands from control PC, the robot will autonomously generate agonistic behaviors to attack rats during the interaction. It is definitely that
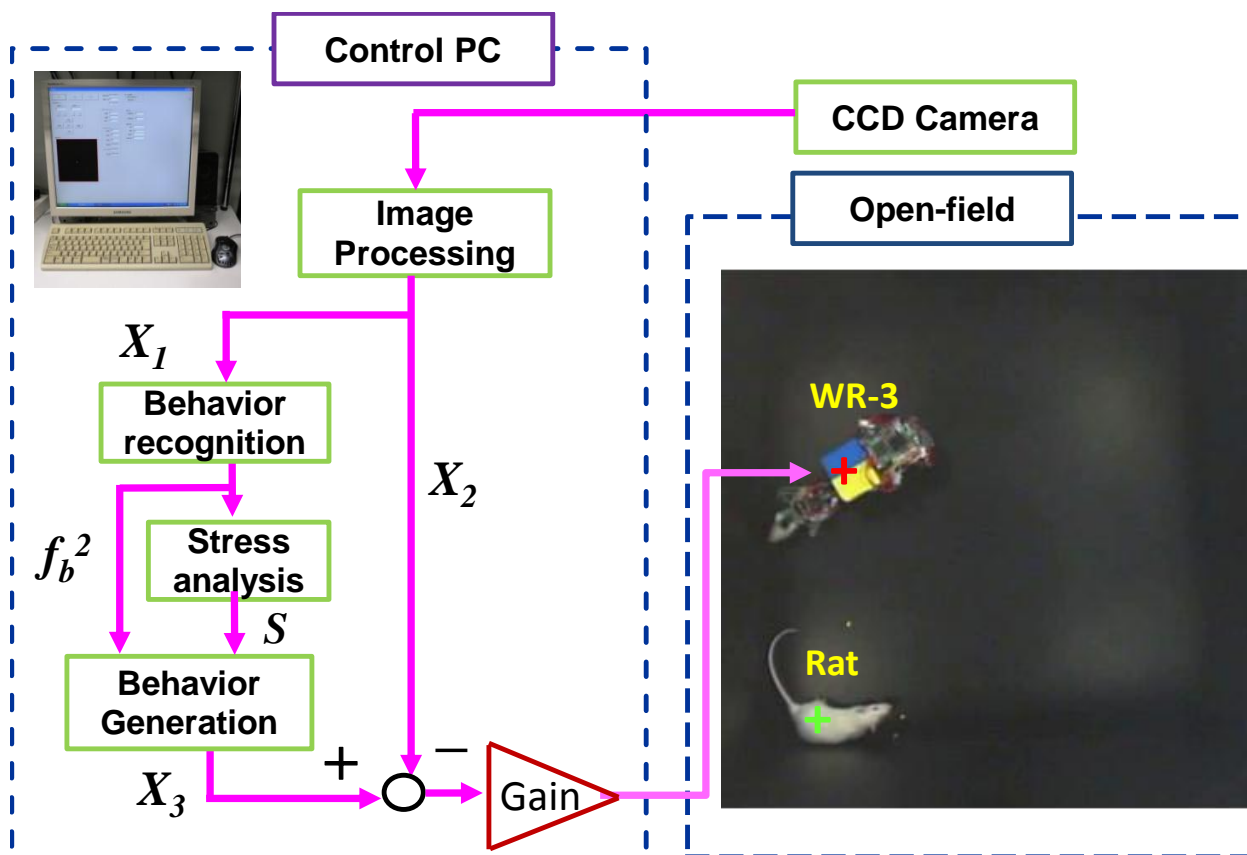
Figure 5.2 Experiments are conducted between WR-3 and rats in the open-field

the rats will avoid the robot during the agonistic interaction, so the robot should be move at high speed enough to guarantee the agonistic interaction.

### 5.2.2 Experimental Protocol

These male rats (2-week old F344/Jcl [124]) arrived at the laboratory with their mother. Since then, each litter was bred in a cage with their mother. All rat subjects used in the experiment were divided into 2 groups, with 6 rats in each group (Si, Nsi, i=1...12). The experimental procedures for the rats of each group are shown in Table 5.1 ( ). During the stress

Table 5.1 Experiment conditions for different group rats

| Group | Stress exposure (10 min) <3-week> 5 days | Evaluation test (10 min) <8-week> 3 days | Scored parameters |
|---|---|---|---|
| Group S | Agonistic | Evaluation | $a_m \; f_r \, f_g \;\; d_{rb\text{-}r}$ |
| Group Ns | Neutral | | |
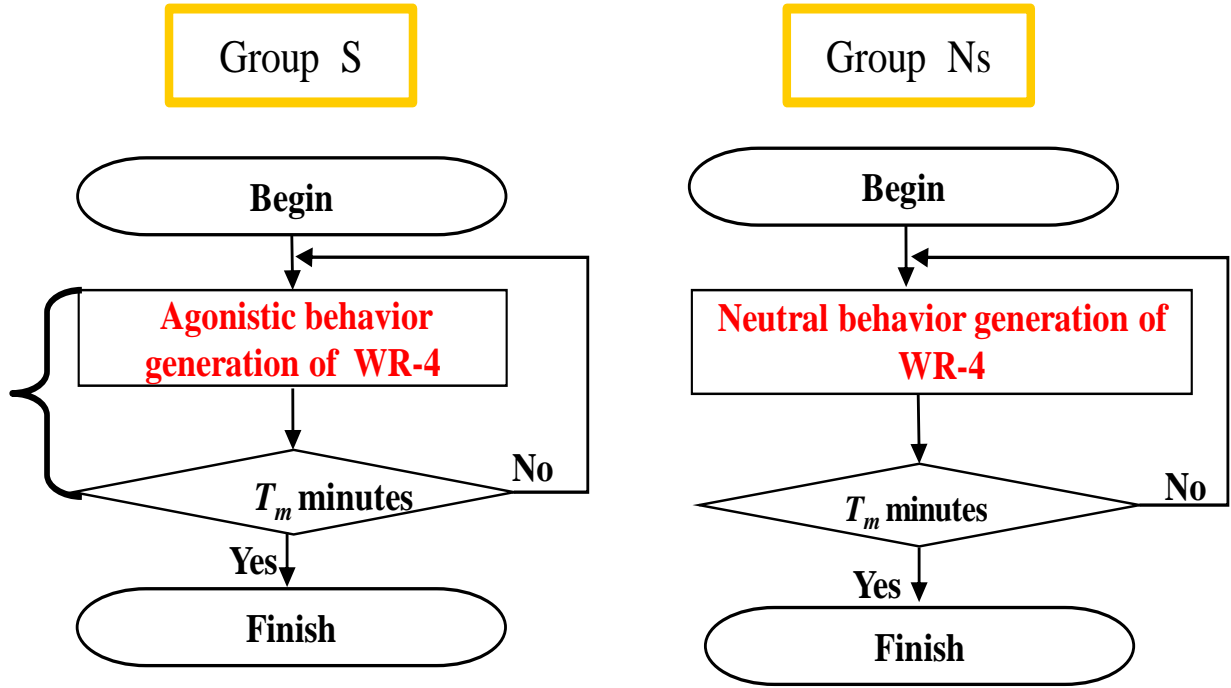
Figure 5.3 Interaction experimental procedures of WR-3 with the rats of Group S and Ns. $T_m$: Time of interaction, here it is 10.

exposure experiments, all the rats weighed similarly to each other (50~60 g).

As described in Chapter 4, the robot can autonomously generate behavior corresponding to the rat behavior by using the video based recognition system. The specific behaviors of robot are generated by the two algorithms detailed below.

1) **Agonistic**: when the robot-rat distance is within a range ($0.15\text{m} \leqq d_{rb\text{-}r} \leqq 0.2\text{m}$), the robot will hit the body of rat back and forth repeatedly at 1 second with a speed: if $v_{rat} = 0$, $v_{robot} = 0.1\text{m/s}$, else $v_{robot} = 0.2\text{m/s}$. When $d_{rb\text{-}r} > 0.2\text{m}$, the robot will chase the rat with the speed $v_{robot} = - v_{rat} + 0.1\text{m/s}$. When $d_{rb\text{-}r} < 0.15\text{m}$, the robot will move back with the speed $v_{robot} = 0.05\text{m/s}$.

2) **Neutral**: the robot continuously follows the rat, i.e., interact neutrally with rats. When $0.2\text{m} \leqq d_{rb\text{-}r} \leqq 0.25\text{m}$, $v_{robot} = v_{rat}$. When $d_{rb\text{-}r} > 0.25\text{m}$, $v_{robot} = v_{rat} + 0.05\text{m/s}$. When $d_{rb\text{-}r} < 0.2\text{m}$, the robot will move back with the speed $v_{robot} = 0.05\text{m/s}$. When $v_{rat} > 0.4\text{m/s}$ and $d_{rb\text{-}r} > 0.2\text{m}$, $v_{robot} \leqq 0.4\text{m/s}$.
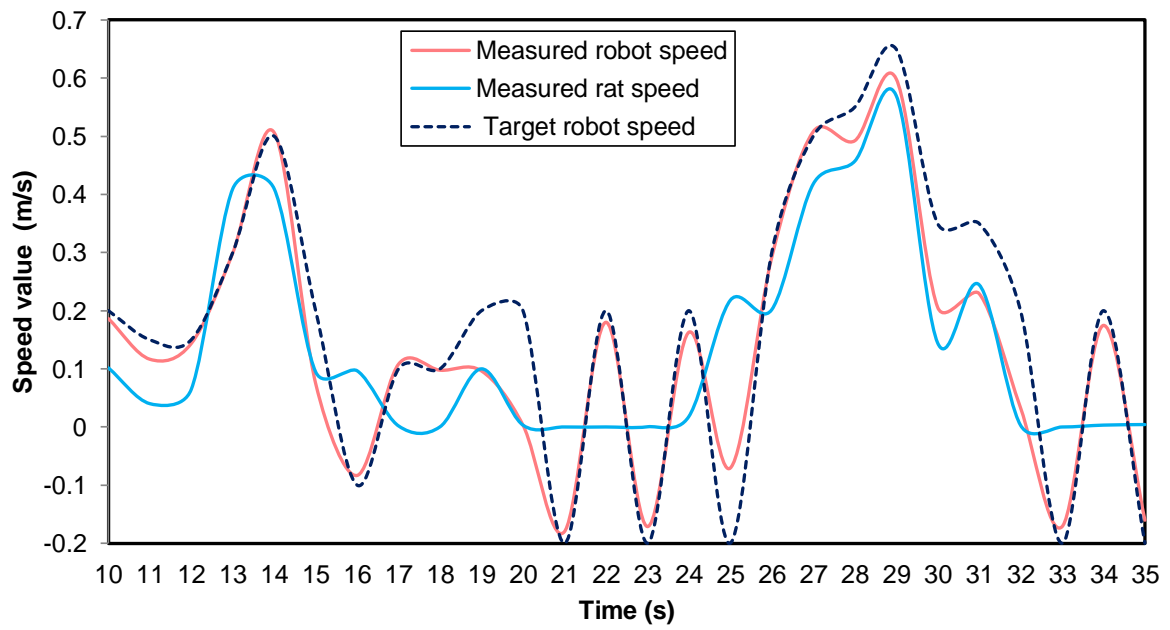
(a) The speed of the robot and a rat
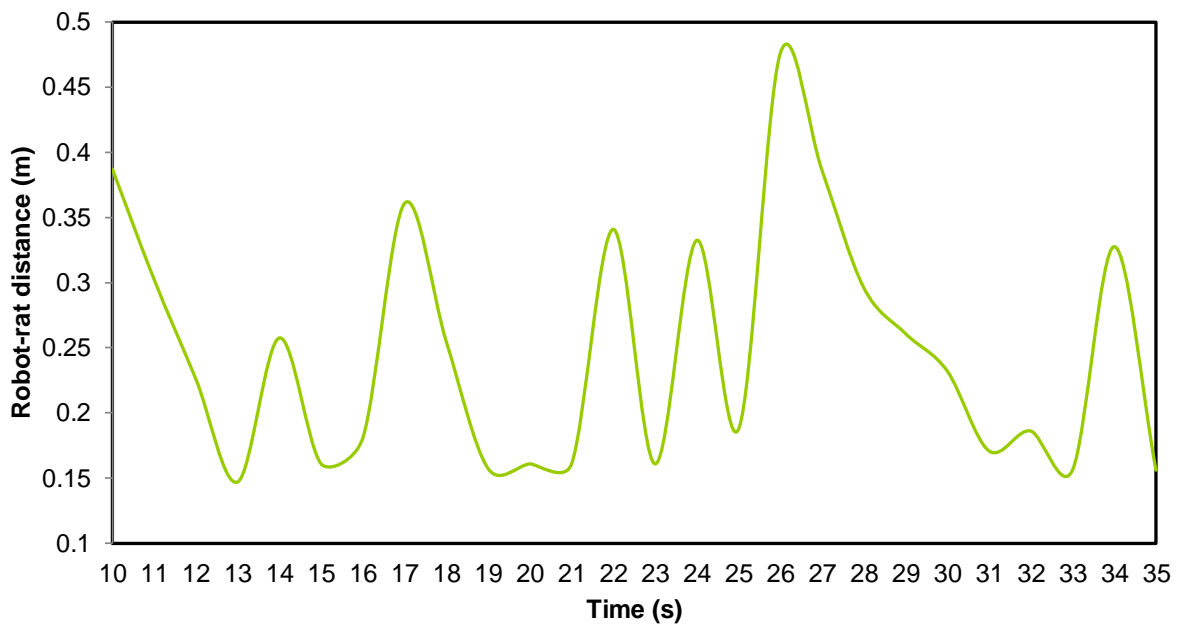


(b) The distance between the robot and a rat

Figure 5.4 The speed of the robot and a rat, and robot-rat distance during one of the stress exposure experiment. The speed of the robot was controlled near the target value. The tremendous variation in the robot-rat distance suggests the rat may receive lots of stress and then moves avoid the robot.
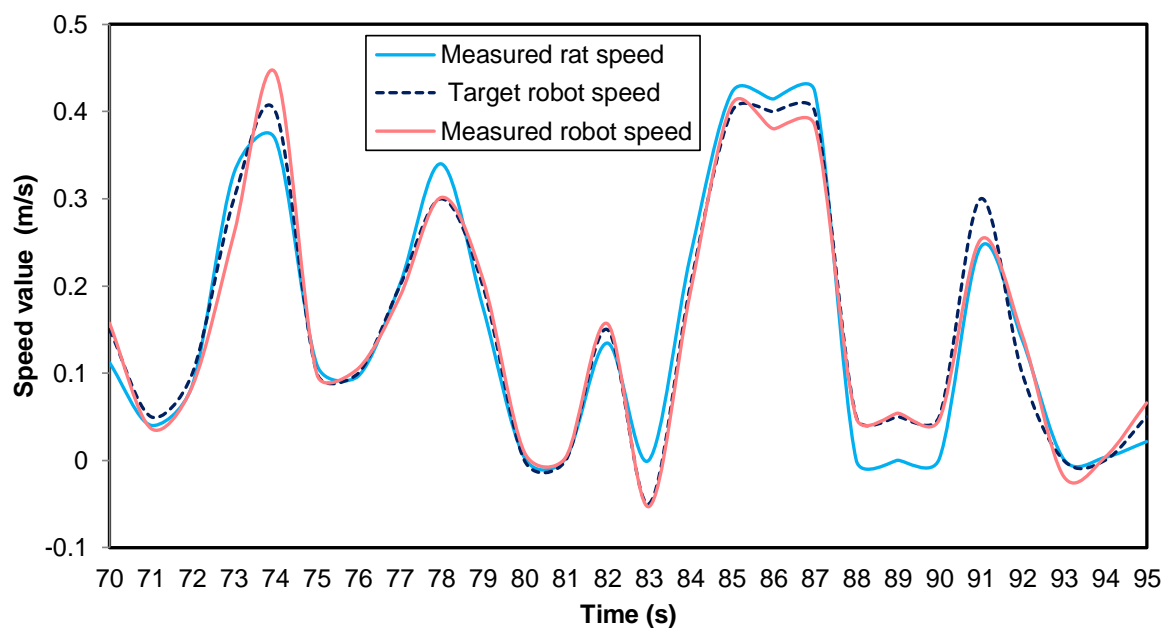
(a) The speed of the robot and a rat
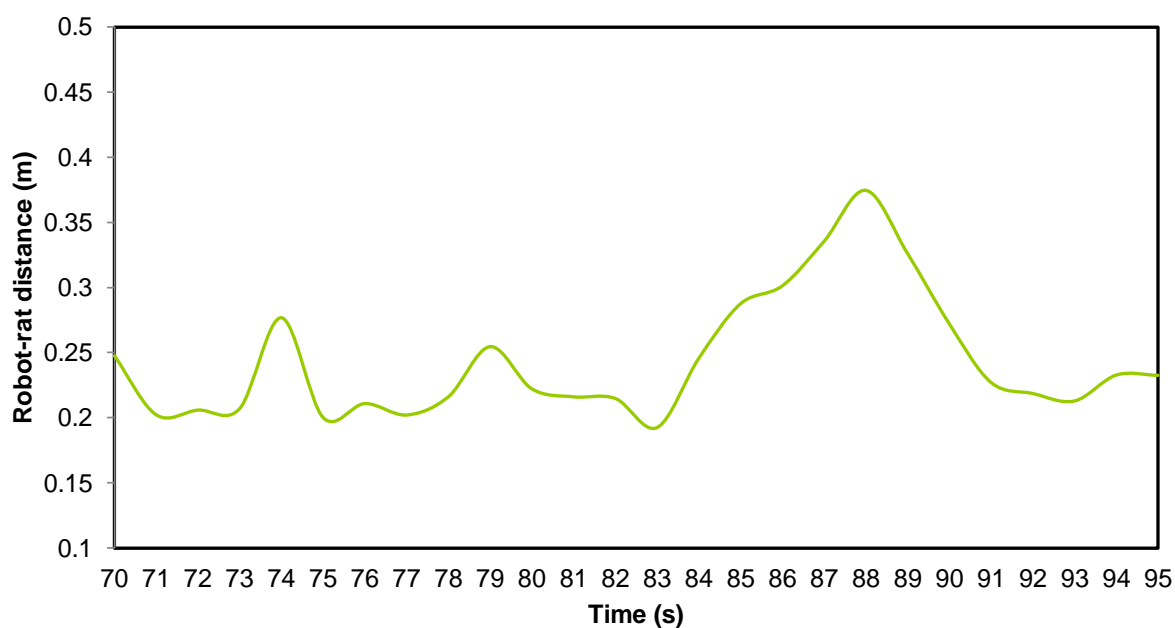


(b) The distance between the robot and a rat

Figure 5.5 The speed of the robot and a rat, and robot-rat distance during one of the neutral interaction. The speed of the robot was controlled well near the target value. There is no great change in the robot-rat distance
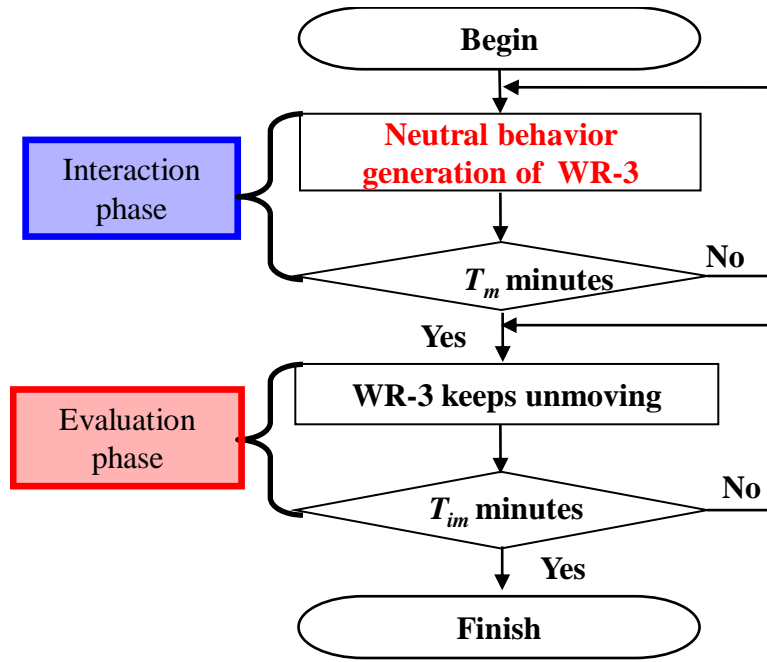
Figure 5.6 Procedure of the evaluation test. ($T_m$=7min, $T_{im}$ =3 min)

With the specific definition of the above two types of behaviors, the robot chases the rat quickly and hit the body of rat when exhibiting agonistic behavior. There is high possibility that the rat will receive lots of stress during this kind of interaction, which can be considered as stress exposure experiment consequently. The speed of the robot is controlled based on the behavior generation algorithm. Figure 5.4 shows part (within 25s interval in one experiment) results of the speed of one rat and the robot, and robot-rat distance during the stress exposure experiment. There are some errors though, the robot speed was controlled quite near the target value. The tremendous variation in the robot-rat distance suggests the rat may receive lots of stress and then moves avoid the robot. When the robot interacts neutrally with rats, the speed of the robot becomes slower. The results obtained in 25s interval of one of the experiments can be seen in Figure 5.5. For the neutral interaction, during most of the time, the robot follows the rat softly. The rat speed in the neutral interaction changed slower than that in the agonistic interaction. Likewise, the robot-rat distance changed not so frequently when the rat was exposed to the robot. Given such kind of difference, the behaviors of the rats can be assumed to be different in the two types of interactions.

　　Regarding the stress exposure experiments, WR-3 acted agonistic and neutral behaviors to the rats of Group S and Ns respectively. The same experiment was continuously conducted

(a) Amount of movement



(c) Frequency of rearing



(d) Robot-rat distance

Figure 5.7 The total mean of the parameters of each group were compared by Student's t-test ($n = 6$; *: $p < 0.05$; **: $p < 0.01$). IP: interaction phase, EP: evaluation phase

for 5 days. When the rats became mature, the evaluation test was conducted to measure the motion variables of them. As shown in Figure 5.6, in the first $T_m$ minutes, WR-4 acted neutral behaviors to the rats, which is called interaction phase. In the remaining $T_{im}$ minutes, the robot stayed immobile in the center of the open-field, which is named as evaluation phase. For each rat, the same experiment was conducted once in one day, and with total duration of 3 days. All the motion parameters were measured based on the recognition system introduced in Chapter 4.

### 5.2.3 Results and Analysis

The author scored the rearing frequency $f_r$, body grooming frequency $f_g$, and the amount of movement $a_m$ in rats during the interaction phase, as well as the robot-rat distance $d_{rb-r}$ during the evaluation phase. The robot-rat distance may vary with the locomotion of the robot in the interaction phase, especially for the experiments in which the rats were continuously followed by the robot. Therefore this parameter was scored only in the evaluation phase.

After calculating measured results of the parameters, we obtained the mean frequency of acting rearing, grooming behaviors and approaching the robot, the mean robot-rat distance and the mean amount of movement in each rat with respect to date. Likewise, the total mean values of each parameter with respect to group were calculated. The frequency of body grooming $f_g$ in rats of both groups are quite similar though, $a_m, f_r$ in rats of Group S are significantly less than that of Group Ns, while $d_{rb-r}$ in rats of Group S are significantly more than that of Group Ns (Figure 5.7,). These results suggest that most of the rats of Group S have less activity and show lower preference to the robot than that of Group Ns as expected. Therefore these 3 parameters can be considered as the variables to represent the stress level of rats, i.e., $x_i$ of Eq.2.1 proposed in Chapter 2.

The author performed PCA on the data generated from $a_m, f_r, d_{rb-r}$ of all rats. To ensure the variables have equal range, the author transformed the data to have zero mean and unit variance by the following standardisation equation.

$$x_{si} = \frac{x_i - \mu}{s} \tag{5.1}$$

Where $\mu$, $s$ are the mean and standard deviation of each variable $x_i$ respectively.
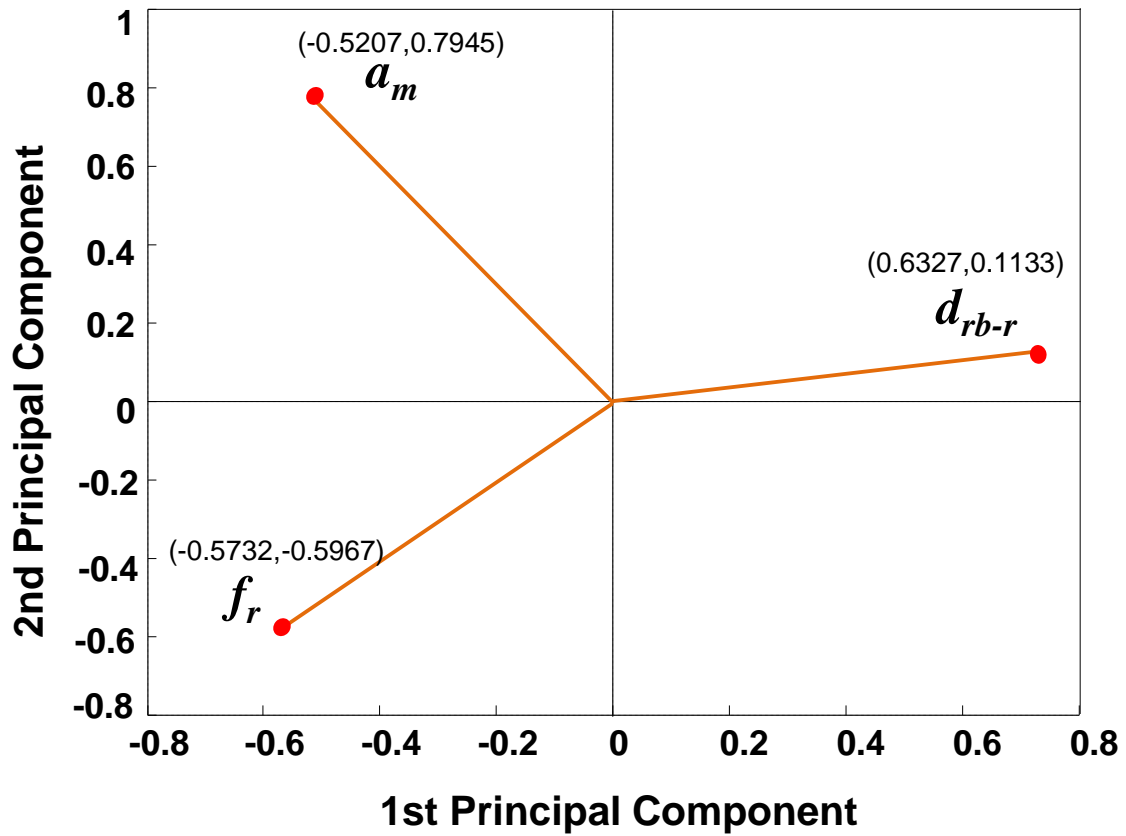
Figure 5.8  Each of the 3 variables is represented by a vector in the coordinate system defined by the first 2 PCs, the direction and length of the vector indicates how each variable contributes to the 2 PCs. The first PC coefficient $pc_{1i}$ for each variable is the coordinate of each variable in the first principal.

3 PCs were chosen in total, and the percent of the total variability explained, i.e. $r_j$, is 62.01%, 24.3%, 14.65%. In the coordinate system defined by the 2 PCs Figure 5.8), each of the 3 variables is represented by a vector, and the direction and length of the vector indicate how each variable contributes to the 2 PCs. The $pc_{1i}$ is the coordinate of each variable in the first PC coefficient respectively. Given $pc_{1i}$, we can calculate $k_i$ based on Eq.2.2. The calculated coefficients of $a_m$, $f_r$ and $d_{rb-r}$ are, $k_m$= -0.5207, $k_r$= -0.5732, $k_d$= 0.6327 respectively.

Given variables $x_i$ and coefficients $k_i$, the stress level of rats $S$ with respect to each rat can be determined. The rat was probably induced with mental disorder when $S > 0$; on the contrary, we believe that mental disorder has not been induced in rats. As shown in Figure 5.9, in case of Group S, it can be confirmed that all rats except one rat have been shaped with a
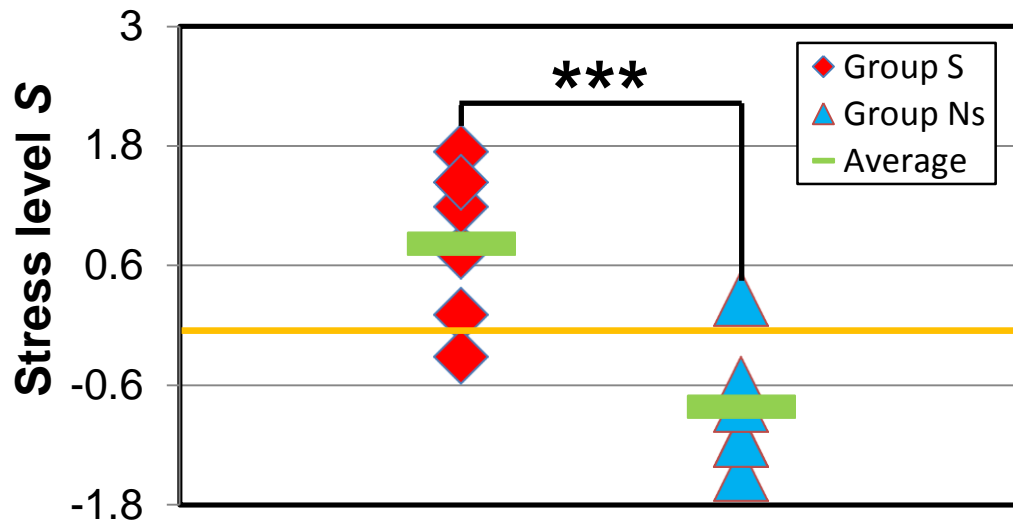
Figure 5.9 Calculated stress level of rats in the robot-rat interaction. Yellow line is the boundary. When the stress level is higher than the line, the rat probably is induced mental disorder, otherwise it is not. ($n = 6$;　***: $p < 0.001$ )
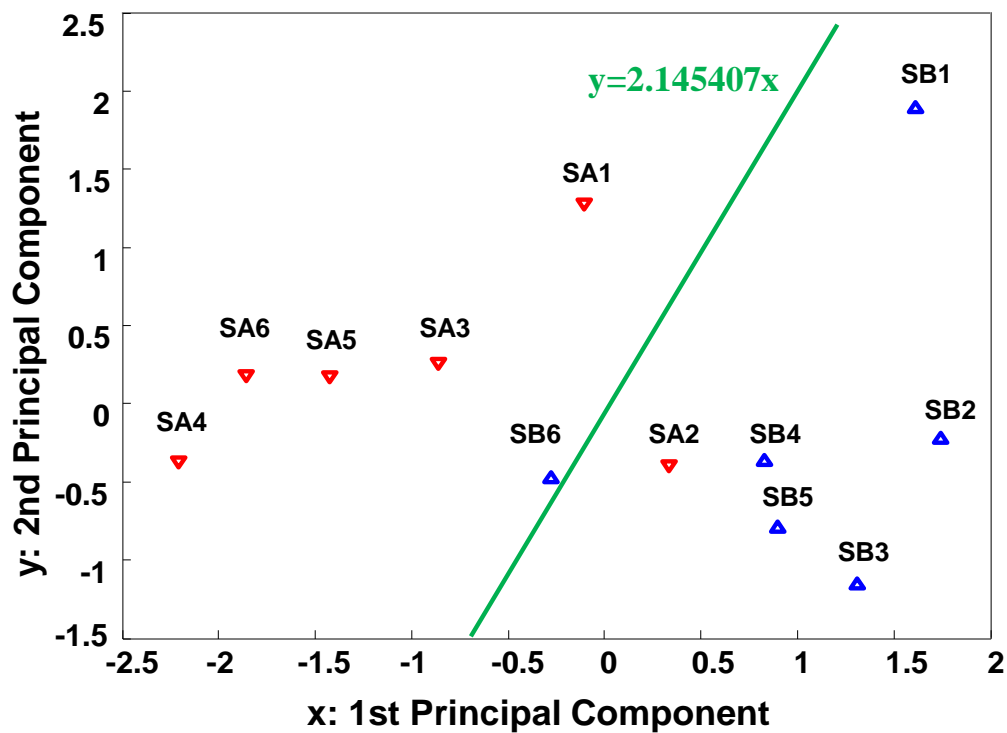


Figure 5.10 The discriminant analysis of Group SA and Group SB based on the first and second principal components.　Regarding each subject, the vertical distance to the discriminant line is proportional to the stress level.
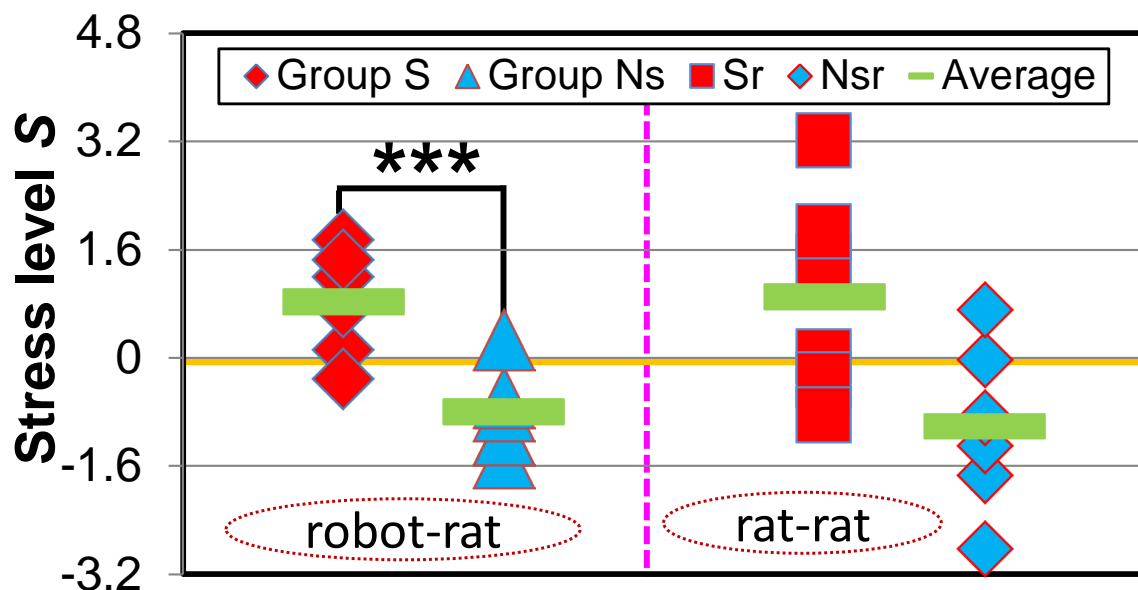
Figure 5.11 Comparison to results of the rat-rat interaction. Robot-rat interaction (left), rat-rat interaction (right). The yellow line is the boundary line. ($n = 6$; ***: $p < 0.001$)

friendly relationship with the robot. Regarding the rats of Group Ns, although $S$ of one rat is unexpectedly more than 0, $S$ of the other rats are less than 0. Comparing averaged results, significant difference between the two groups can be found. The robot behavior could influence rats distinctly, so different robot behavior results in different rat behavior.

To confirm the correctness of the equation, the author conducted LDA on the PC results of the measured parameters. As shown in Figure 5.10, the classified results are almost the same to the results calculated, proving the effectiveness of the derived equation. The success rate is 83.3%, a very high accuracy in animal experiments because the behaviors of living animals are highly sensitive to surrounding environments. So most of the rats of Group S probably were created as models of mental disorder. Therefore the robot-rat interaction system achieves to analyze and control the stress level of rats.

### 5.2.4 Rat-rat Interaction

To confirm the validity and generality of the derived equation, we evaluate it by using the results measured during interaction between real rats. The rat-rat interaction experiments were conducted in the experimental apparatus illustrated in Figure 4.7, the same as robot-rat interaction. 12 rats (3-week old F344/Jcl) divided into 2 groups: Group Sr and Nsr (Sri, Nsri,

i=1...6), were exposed to the stressful and neutral rats (partners) respectively. It is quite likely that the relationships between real rats vary with partners, so preliminary tests were conducted to select a suitable partner for each rat. Consequently, each rat of Group Sr could be guaranteed to be exposed to an agonistic partner, and each rat of Group Nsr interacted with its partner neutrally. For better identification, all the partners were blue-colored during the experiments. Similar to the experimental conditions illustrated in Table 5.1, the stress exposure experiments were conducted when the rats were 3 weeks old. The evaluation tests were conducted when the rats were 7 weeks old. The procedure of evaluation test is the same to robot-rat interaction as shown in Figure 5.6. However, while in the evaluation phase, the partner was replaced by a stuffed rat made of a living, mature real rat. We measured $a_m$, $f_r$, and $d_{r-r}$ (rat-rat distance) during each experiment. After standardizing the measured data, we calculated the stress level of between real rats based on Eq.2.1.

As shown in **Error! Reference source not found.**, 4 rats of Group Sr were successfully haped with friendly relationships with corresponding partners, and 5 rats of Group Nsr were confirmed to interact with corresponding partners neutrally. So the success rate is 67.7%, approximately the same as that of the robot-rat interaction system, revealing the validity and generality of the equation listed in Eq.2.1. In addition, the STDEVP of each group was calculated to evaluate variance. The specific results are: 0.728, 0.561, 1.409 and 1.141 for Group S, Group Ns, Group Sr, and Group Nsr respectively. The variance of robot-rat interaction system is distinctly less than that of rat-rat interaction system.

# 5.3 Discussion

### 5.3.1 Justification of the Experiments

The rats of two groups exposed to agonistic (Group S) or neutral (Group Ns) robot respectively acted differently after the interaction. In general, the rats of Group S tended to be less active and showed lower preference to the robot than that of Group Ns. Therefore, the author assumes that the rats might suffer from mental disorder when receiving agonistic behaviors from conspecific partners. According to the derived linear function, the stress level of each rat has been calculated. The higher the stress level of the rat, the more possibility it may suffer mental disorder. The rats exposed to agonistic partners had higher stress level and probably

can be used as RMMD, which confirmed the validity of the stress exposure experiment. However, the rats exposed to neutral conspecific partners had lower stress level, so the rats received less direct affects in the neutral interaction. Accordingly, the neutral interaction is effective to evaluate the behaviors of rats. Compared the rat-rat interaction, there are less variance of the stress level of rats in robot-rat interaction, which suggests that the robot achieves to control the behavior of rats more effectively. So the robot-rat interaction system is promisingly able to control the rat behavior in the same way as real rats, and to gain better controllability and reproducibility.

### 5.3.2 Problem Statements

Certainly, the current experiment design is not perfect yet. Current experimental system and analysis are mainly received some criticisms detailed below.

Changes in the experimental design may lead to different results. For instance, the number and the ages of subjects, the interaction duration, etc., can be changed and thus various experimental conditions can be available. However, the experiment design might be infinite, it is impossible to conduct experiments that can cover all the condition. The main objective of this research is to develop a novel platform for animal experiments, not to study the behavior of animals. In this point, the findings derived from experimental results are enough to prove the effectiveness of the system. In this experiment, all the subjects are male rats. Probably different results are obtained when using female rats as subjects.

Regarding the analysis of the stress level of rats, only the behavior related parameters were considered. Focusing on the realistic application in the pharmacology, the physiological analysis such as, blood pressure, blood sugar levels, brain changes, etc., should be taken into account. In addition, new insights can be found when implementing anatomical analysis on the rat subjects. Therefore, more comprehensive findings can be obtained when collaborating with some pharmacologists involved.

In the current robot-rat interaction experiment, the smell and sound that definitely exist in the realistic experiment have not been considered. The device that is able to emit the urine-like smell and imitate the sound of rats should be added in the future robot. To describe the advantages of using rat-like robot, more convincing evidence is available when putting a cover similar to rat fur in the robot. Besides, probably more convincing results can be obtained if

the experiments are conducted under varies of conditions, for example, conducting experiments on different weeks of rat subjects, extending the duration of each experiment, putting a robot with multiple rats in the experimental field, etc.

Anyway, the current work provides useful insights and findings for the animal behavior research, and is promising to become one of the animal experimental frameworks in the future.

## 5.4  Summary of this Chapter

In this chapter, based on the vulnerability hypothesis, the author developed a novel experiment system to create RMMD by using robot technology. The stress induced from social interaction can be considered as one of the most important causes to the mental illness.

1) To simulate the social interaction between real rats and improve the controllability and reproducibility, a rat-like robot was used to interact with the rat subjects in the open-field. The rats of one group were exposed to the robot that exhibited agonistic behaviors. As comparison, the rats of the other group were exposed to the neutral robot. Based on the measured motion parameters, significant differences were found the rats in two groups. So the robot could influence the behavior of rats to some degree.

2) From the calculated results by using the linear model of stress level, the rats exposed to agonistic robot tended to be high anxiety. The results show that this kind of experiment system is able to create RMMD with high reproducibility and controllability.

# Chapter 6

# Friendly Interaction between the Robot and Rat

## 6.1 Introduction

### 6.1.1 Background

Regarding the three types of interactions, the agonistic interaction was introduced in Chapter 5 for the development of RMMD, and the neutral interaction is usually conducted for comparison with another two types of interactions. In this chapter, the author mainly discusses the friendly interaction, which might possible to reduce the stress of rats, in contrast to agonistic interaction. It seems easy to assume that the robot plays as the role of friendly partner should be active firstly. Otherwise, it cannot even attract the attention of rats, not to mention drawing their interests. [42] Showed that rats exposed to active partners became more social active. So the social activity of rats exposed to friendly robot (active partner) will possibly rise. The activity of rats are determined mainly by the amount of movement am, rearing frequency $f_r$, grooming frequency $f_g$ [29], etc. Besides, the author considers that the rat's preference to the robot is a significantly important index to indicate friendliness. If the rats show more preference to the robot, they should move toward and approach the robot more frequently (refers to robot-rat distance $d_{rb-r}$, etc.) [42].

The linear mathematical model representing the stress level of rats was specified in Chapter 5. In this chapter, to reduce the stress of rats, the robot is controlled to interact with rats friendly. The stress level of each rats were calculated based on the specified linear mathematical model. Likewise, the stress levels of rats in the rat-rat interaction were calculated by this linear model. Similar results were found in robot-rat and rat-rat interaction, suggesting the effectiveness of robot-rat interaction system.

### 6.1.2 Objective

This chapter is to reduce the stress of rats by interacting with the robot in a friendly way. The friendly robot-rat interaction is possible to improve the activity of rats, and the preference to the robot, which will be proved by the experiments as well. The specified linear mathematical model is used to calculate the stress levels of rats in this experiment. In addition, the similar interaction will be conducted between real rats, and the stress levels of rat subjects will be calculated to evaluate the validity of robot-rat interaction, the generality of the linear mathematical model.

## 6.2  Friendly Interaction between WR-4 and Rats

### 6.2.1 Experiment Setup

The experimental setup is shown in Figure 5.2. The rat and robot are put into a 700×700 mm of the rat and robot can be detected by a CCD camera (solution: 640×480 pixels) affixed on the top of open-field. Especially the motion parameters and behaviors of rats can be classified and analyzed by the recognition system proposed in [108]. Receiving the commands from control PC, the robot will autonomously imitate the behaviors of rats during friendly interaction.

### 6.2.2 Experimental Protocol

The experiment is conducted to make the rats be shaped with a friendly relationship with the robot. The robot imitates behaviors corresponding to the behaviors of rats during the experiment. As mentioned in Chapter 4, the rat is considered to be attracted by the robot through behavior imitation in the interaction. All rats used in the experiment were divided into 2
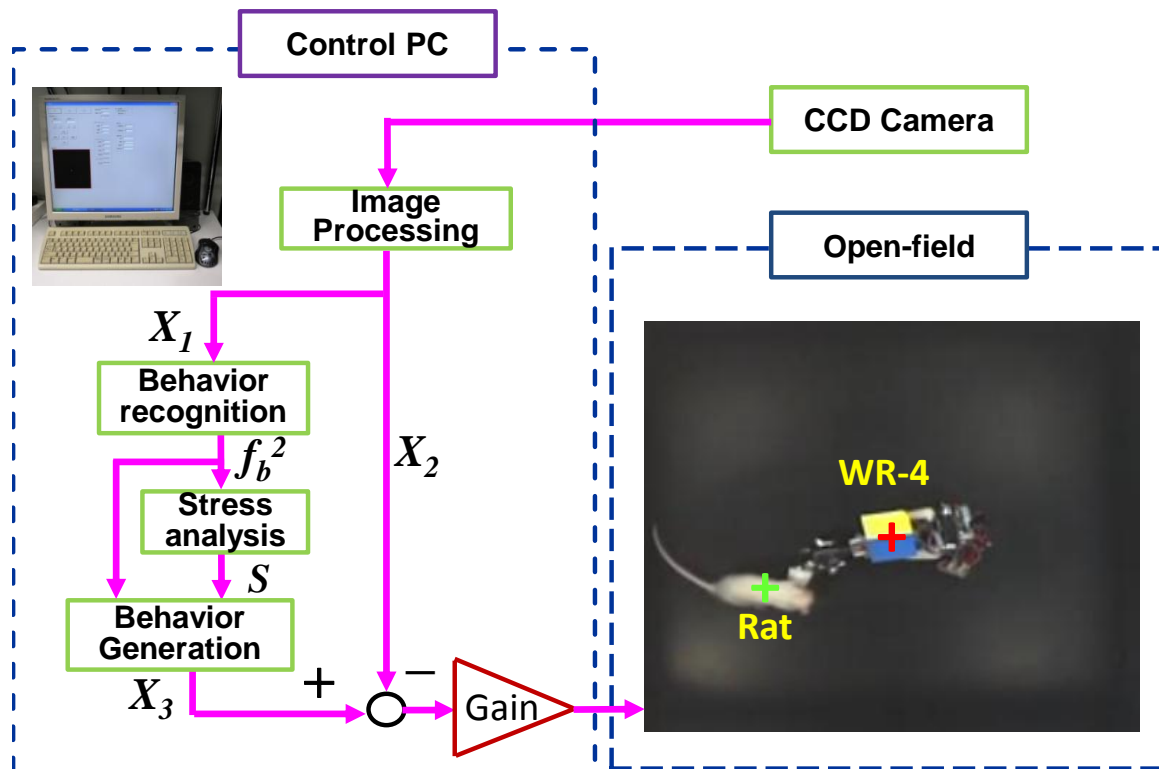
Figure 6.1 Friendly interaction experiment is conducted between WR-4 and living, mature rats in an open-field. WR-4 is recognized through the color board fixed on its back.

groups, with 6 7-week old F344/Jcl [124] rats in each group (Fi, Nfi, i=1...6). All the rats are male, weigh about 200 g and are reared in the same housing conditions during the experimental days. Specific experiment conditions are shown in Table 6.1. Every day all the rats are put with the robot for interaction with duration of 15 min. The same experiment is continuously conducted 6 days.

Table 6.1 Experiment conditions for different group rats

| Group | Interaction (15 min) <7-week> 6days | Scored parameters |
|---|---|---|
| Group F | Friendly | $a_m$ $f_r$ $d_{rb-r}$ |
| Group Nf | Neutral | |

The specific experimental procedures for each group can be seen from Figure 6.2. In the first $T_m$ minutes, WR-4 acted friendly and neutral behaviors to the rats of Group F and Nf respectively. In the remaining $T_{im}$ minutes, the robot stayed immobile in the center of the open-field. The same experiment was continuously conducted for 6 days.

The speed control of the robot is the same for both neutral and friendly interaction. For the detail, please refer to the Chapter 5. Part results of the speed of the robot and one rat, the robot-rat distance in the friendly interaction is shown in Figure 6.3. When comparing with these results in the neutral interaction as introduced in the Chapter 5, all the results are quite near. Difference between these two types interaction is that, the robot only follows the rats all the time in neutral interaction. While in the friendly interaction, the robot not only follows the rat but also acts rearing/grooming when the rat rears/grooms.

Similar to stress exposure experiments, rearing frequency $f_r$, and the amount of movement $a_m$ in rats during the interaction phase, and the robot-rat distance $d_{rb-r}$ during the evaluation phase were automatically scored based on the recognition system.
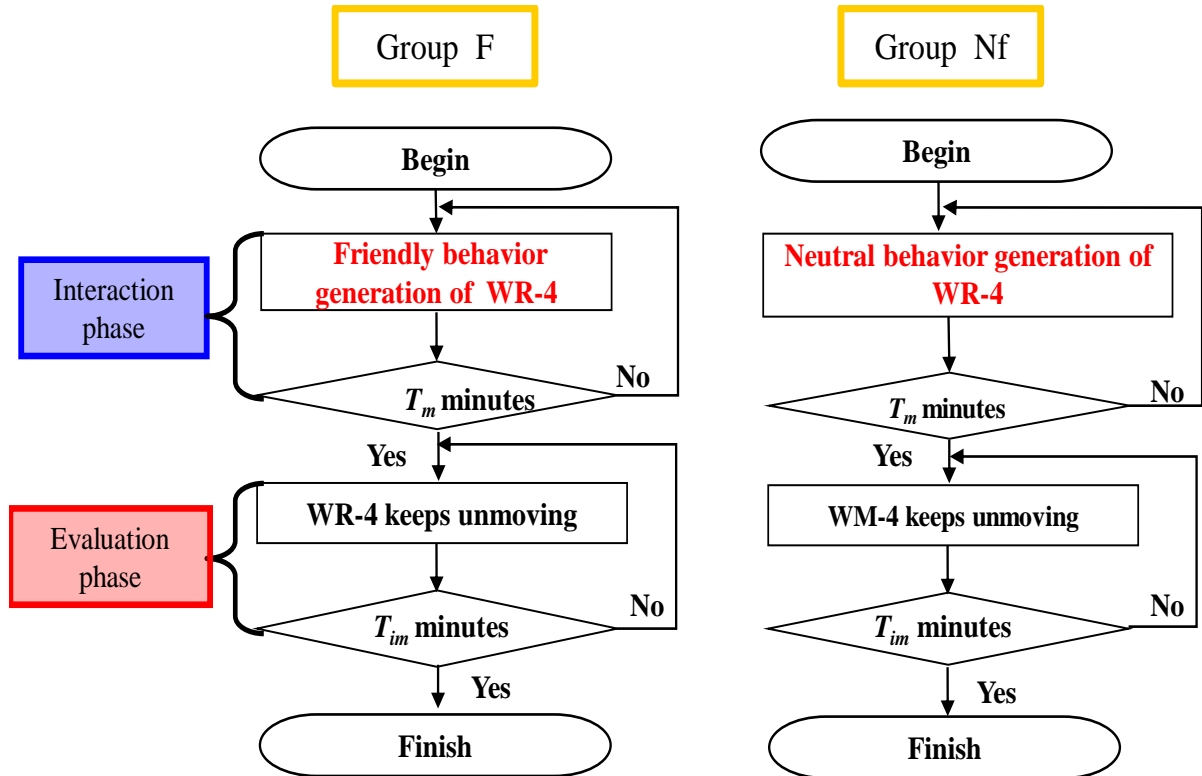


Figure 6.2 Interaction experimental procedures of WR-4 with the rats of F and Nf group. $T_m$: Time of interaction, here it is 10; $T_{um}$: Time of robot keeping unmoving, here it is 5.
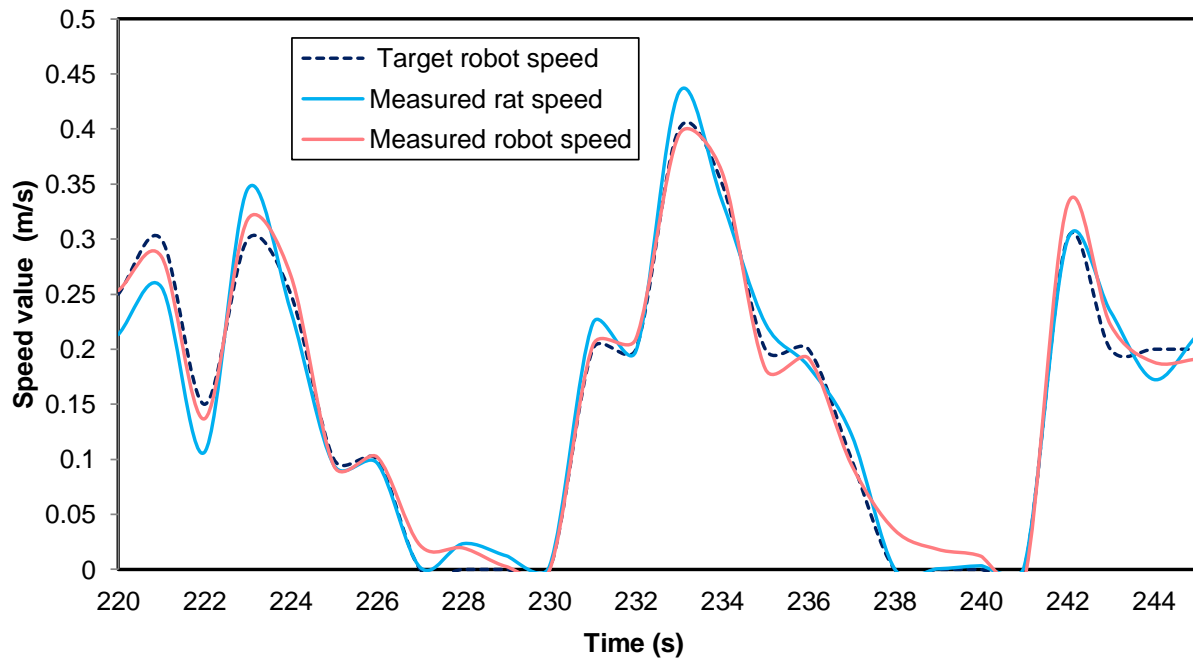
(a) The speed of the robot and a rat
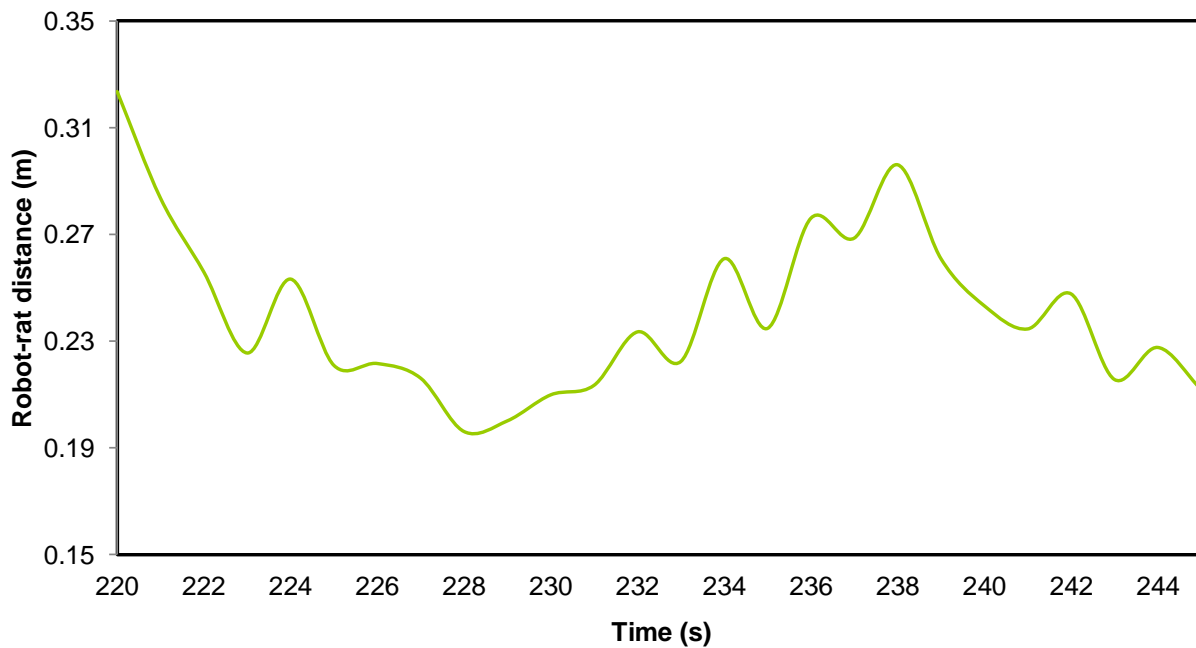


(b) The distance between the robot and a rat

Figure 6.3 The speed of the robot and a rat, and robot-rat distance during one of the friendly interaction. The speed of the robot was controlled quite near the target value.

## 6.2.3 Results and Analysis

Based on the measured results of the parameters, the mean amount of movement , the mean frequency of acting rearing and the mean robot-rat distance were calculated for each rat with respect to date. Likewise, the total mean values of each parameter with respect to group were calculated. As shown in Figure 6.4, $a_m$ in rats of Group F are a little more than that of Group Nf, $f_r$ in rats of Group F are significantly more than that of Group Nf, while $d_{rb-r}$ in rats of Group F are significantly less than that of Group Nf. The higher value of $a_m$ and $f_r$ suggest that most of the rats of Group F have more activity than that of Group Nf. The results meet the findings described in [42].  Furthermore, the higher value of $d_{rb-r}$ reveals that in rats of Group F shows higher preference to the robot. Thus these 3 parameters can be considered as the variables to represent the degree of robot-rat friendliness. As confirmed in Chapter 5, these parameters can be used to represent the stress level of rats as well. The differences in the results are due to the different behavior of the robot when interacting with rats of Group F and Nf. So the author assumed that the behavior of rats could be controlled by controlling robot behavior. All the measured values were standardized using E.q.5.1 to guarantee all the data lie in the same scale.

Given coefficients $k_i$ ($k_m$= -0.5207, $k_r$= -0.5732, $k_d$= 0.6327) determined in Chapter 5, and the scaled $a_m$, $f_r$ and $d_{rb-r}$, the stress level of each rat can be calculated. As shown in Figure 6.5, there are 4 rats of both Group F and Nf have low stress level ($S<0$). Furthermore, 4 rats of Group F have lower stress level than the rats of Group Nf. So the stress friendly interaction between robot and rats might be able to reduce the stress of rats to some degree.

On the other hand, given the boundary of friendliness $S$=-0.5, 4 rats of Group F are considered to be shaped friendly relationship with the robot. Regarding the rats of Group Nf, 1 rat: $S<$-0.5, 3 rats: $-0.5 \leqq S \leqq 0$. If $S$ lies in the range [-0.5, 0], the rat is assumed to be shaped a neutral relationship with the robot. So 3 rats of Group Nf are thought to be shaped with neutral relationship with the robot. The social relationship in rats is considered as a part of rat sociality. Therefore the robot-rat interaction system probably achieves to analyze and adjust the rat sociality as well.
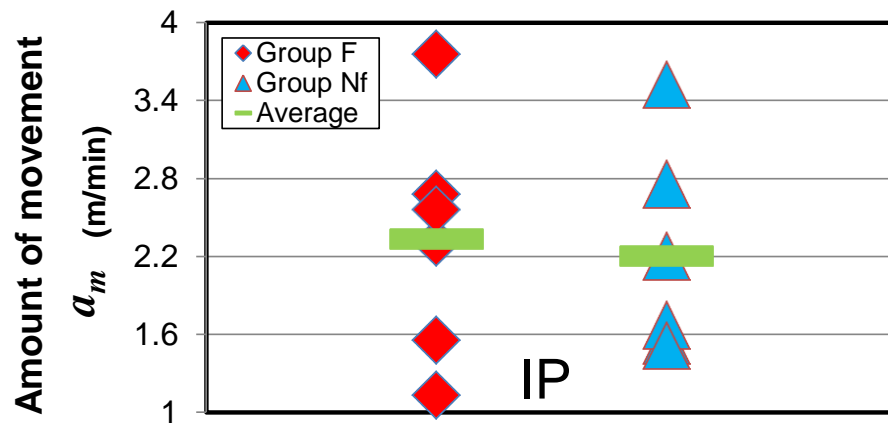
(a) Amount of movement
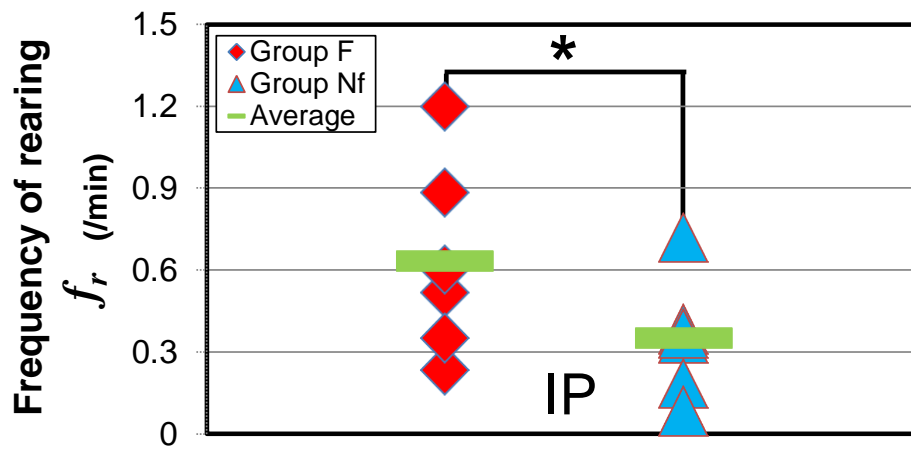


(b) Rearing frequency
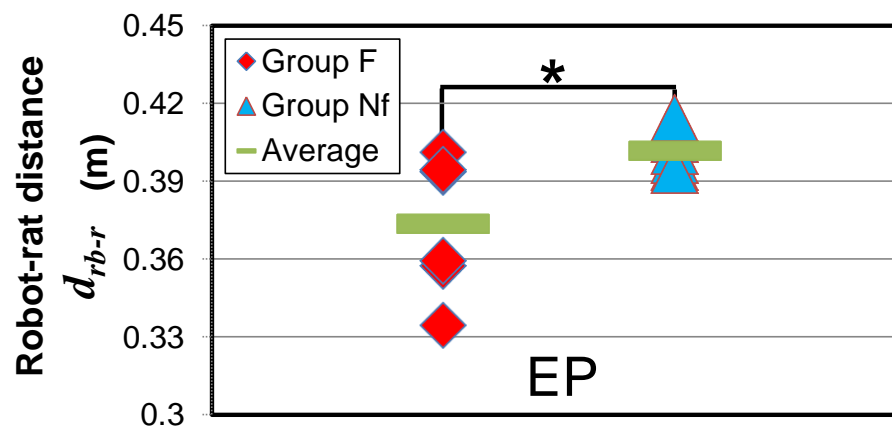


(c) Robot-rat distance

Figure 6.4 The mean frequency of acting rearing, the mean robot-rat distance and the mean amount of movement in each rat with respect to date. All the results were compared by Student's t-test ($n = 6$; *: $p < 0.05$). IP: interaction phase, EP: evaluation phase

Figure 6.5 The stress level of rats. The yellow line is the boundary as described in Chapter 5. Green line is the boundary of friendliness.



Figure 6.6 The stress level of rats in the robot-rat interaction (left), rat-rat interaction (right). There is less variance of the results in robot-rat interaction.

### 6.2.4 Rat-rat Interaction

To confirm the validity and generality of the derived equation, the similar interactions were conducted between real rats. 12 rats (7-week old F344/Jcl) divided into 2 groups: Group Fr and Nfr (Fri, Nfri, i=1...6), were exposed to the friendly and neutral rats (partners) respectively. It is quite likely that the relationships between real rats vary with partners, so preliminary tests were conducted to select a suitable partner for each rat. Consequently, each rat of Group Fr can be guaranteed to interact with corresponding partner in a friendly way, and each rat of Group Nfr can be guaranteed to interact with its partner neutrally. For better identification, all the partners were blue-colored during the experiments. Similar to the robot-rat interaction procedure illustrated in Figure 6.2, the rats interacted with living partners during the interaction phase. However, while in the evaluation phase, the partner was replaced by a stuffed rat made of a living, mature real rat. The same experiments were continuously conducted for 6 days as well. The $a_m$, $f_r$ and $d_{r-r}$ (rat-rat distance) were measured during each experiment. After standardizing the measured data, the stress level of each rat was calculated based on Eq.2.1.

As shown in Figure 6.6, 4 rats of both Group Fr and Nfr have low stress level ($S<0$). Among these rats, 3 rats of Group Fr were successfully shaped with friendly relationships with corresponding partners ($S<-0.5$), and 3 rats of Group Nfr were confirmed to interact with corresponding partners neutrally ($-0.5 \leqq S \leqq 0$). So the success rate is approximately the same as that of the robot-rat interaction system, revealing the validity and generality of the equation listed in Eq.1. In addition, the STDEVP of Group F, Group Nf, Group Fr and Group Nfr are 0.719, 0.534, 1.069 and 0.673 respectively.

# 6.3  Discussion

### 6.3.1 Justification of the Experiments

According to the experimental results, the rat subjects, which interact with the robots in a friendly way, showed higher activity and preference to the robot. So the rats were influenced by the robot in the way as the experimental objective. One of the main reasons is that the control of the robot behavior achieves to control the behavior of rats. Based on the linear mathematical model derived in Chapter 5, the stress levels of all the rat subjects were calculated. The lower stress level in the rats exposed to friendly robot suggests that the robot achieves to

decrease the stress level of rats. In other words, the stress tolerance of rats exposed to friendly robot might become higher during the interaction. In the future, the friendly interaction can be used to improve the stress tolerance of RMMD.

Comparing with the rat-rat interaction, the less variance of the calculated stress level in robot-rat interaction suggests that the robot achieves to control the behavior of rats more effectively. So the robot-rat interaction system is promising to adjust the stress level of rats in the same way as real rats, and even gain better controllability and reproducibility. Therefore, the robot is able to decrease the stress level of rats by exhibiting friendly behaviors. With the findings described in the Chapter 5, the robot is also able to increase the stress level of rats by exhibiting agonistic behaviors. So the robot is considered to be able to adjust the behavior and the stress level of rats quantitatively and effectively.

### 6.3.2 Problem Statements

As discussed in the Chapter 5, more realistic results may be obtained when considering the effects of smell and sound, as well as the fur. Besides, to improve the generality of results, different experimental conditions should be considered, such as conducting experiments on different weeks of rat subjects, extending the duration of each experiment, putting a robot with multiple rats in the experimental field, differences between male and female subjects, etc. Besides behavior analysis, anatomical analysis, bioanalysis should be conducted to provide more comprehensive evidences. But the current work opens novel insights for animal behavior research in the future and possible reforms for the research in animal behavior in particular.

## 6.4  Summary of this Chapter

In this chapter, the rat-like robot WR-4 was used to interact with real rats to reduce the stress level of rats. The summary of this chapter can be concluded as the following two aspects.

1) All the rat subjects were divided into two groups to interact with friendly and neutral robot respectively. During each interaction, the rearing frequency $f_r$, and the amount of movement $a_m$ in rats during the interaction phase, and the robot-rat distance $d_{rb\text{-}r}$ during the evaluation phase were measured. Substituting these parameters into the specified mathematical model, the stress level of each rat was calculated. The results con-

firmed the generality of the mathematical model, and the effectiveness of the proposed experimental system.

2) The similar interaction experiments were conducted between real rats as well. The distribution of the stress level of rat subjects was quite similar to the robot-rat interaction. So the robot based novel experiment system is able to replace the conventional animal experimental system for some potential application.

# Chapter 7

# Conclusions and Future Works

## 7.1 Conclusions

In this thesis, the author proposed to use an intelligent robotic system to study the behavior of rats. The social interaction between rats is significantly important for the study of rat behavior, thus the robot-rat interaction is the focus of this thesis. In the robot-rat interaction, the relationships between robot behavior, rat behavior, and stress level of the rat are able to be represented by specific mathematical models. This thesis introduced the current progress of this research, in which the relationship between rat behavior and the stress level of rats was specified. Aiming to improve the reproducibility and controllability, the rat-like robot furnished with a recognition system has been used to interact with rats. Based on the specified mathematical model, the stress level of rat subjects exposed to the agonistic robot were high, and these rats are possibly to be created as RMMD. Likewise, the friendly relationship between the robot and rats has been created by conducting friendly interaction, which is promisingly to reduce the stress of rats. The concluded contents of each chapter are described as follows.

Chapter 1 introduces the research background, objectives. Afterwards, a novel methodology is described roughly. Finally, this chapter outlines the organization of this thesis.

Chapter 2 reveals that the complicated relationships among rat behaviors, rat behavior and stress in robot-rat interaction can be represented by specific mathematical models. In this research, only the robot is considered as the unique stimuli that can change rat behavior in this system. Likewise, the robot is thought to be able to influence the stress level of rats by inter-

acting with them. At first, the author proposed to derive the functional relationship between the behavior and stress level of rats based on previous research and numerous experimental results. The stress has significantly close influence in the mental disorder, so it is the focus of this thesis. According to previous research results, the stress level of rats can be represented by the linear combination of motion variables such as the amount of movement, the frequency of rearing, body grooming behaviors, the distance between rat subject and partner. Principal component analysis (PCA) is employed to specify the coefficients of each variable in the linear mathematical model. Likewise, linear discriminant analysis (LDA) is used to confirm the effectiveness of the specified linear mathematical model.

Chapter 3 introduces the design and development of three rat-like mobile robots. A quadruped walking robot called WR-2 was designed similarly with the same size as a mature rat. This robot moved at a very low speed and could not rotate as naturally as real rats. As an improvement, a wheel-legged robot called WR-3 endowed with higher moving speed and better imitation of rat behavior was developed. However, limited moving range of waist and neck of WR-3 caused linear bend posture, which is different with the curved bend posture of rats. Given this lack of a suitable experimental biomimetic robot platform, it is essential to develop a robot that can sufficiently imitate the behaviors of a rat. Building on the experiences gained from previous robot prototypes, to propose a multi-bendable body, which is capable of moving more steadily and bending more similarly as living rats, the improved robot called WR-4 was developed. WR-4 achieves to the bending posture as real rats due to the 6-bar linkage mechanism in the waist and 4-bar linkage mechanism in the neck.

Chapter 4 describes an automated video processing system to replace the traditional manual annotation, as well as to improve the adaptivity of the rat-like robot to autonomously interact with rats. The image processing based recognition system contributes to recognize and the behavior of rats. The robot behaviors are generated based on the recognized rat behavior to meet the purpose of experiments. In general, the robot is able to generate agonistic, friendly and neutral behaviors respectively, to create agonistic, friendly and neutral relationships with rats accordingly. Namely, the robot could change its behavior corresponding to experimental purpose.

In Chapter 5, stress exposure experiments are conducted to create rat models of mental disorder by using WR-3 robot. The results confirmed the successful development of RMMD, which exhibited fewer activities and behaviors during mature period when exposed to a ago-

nistic robot during immature period. Based on the experimental results, the coefficients of the linear function representing the stress level of rats described in Chapter 2 were determined. Likewise, this model was used to calculate the stress level of rats exposed to agonistic conspecifics. The results are confirmed to be similar to robot-rat interaction system. Furthermore, compared to rat-rat interaction, there is less variance of the results in robot-rat interaction, which suggests the latter has better reproducibility. Also the usefulness of the robot agent in the social interaction is confirmed.

In contrast to Chapter5, Chapter 6 introduces friendly interaction experiments conducted to create friendly relationship between rats and the WR-4 robot. The author used the linear mathematical model specified in Chapter 5 to calculate the stress level of rat subjects. The results show that the friendly interaction is able to reduce the stress of rats. Likewise, the author successfully proved the effectiveness of the robot-rat interaction by comparing with the results from friendly interaction conducted between real rats. In the final of this chapter, the author discussed the results of Chapter 5 and Chapter 6 comprehensively. Therefore, based on the interaction modeling, the friendly or agonistic relationship with rats could be created at will.

In conclusion, this thesis demonstrates an intelligent robotic system that can be used to interact with rats in the social interaction. The robot is developed with rat-like shape and is able to imitate the behavior of rats based on the modeling body structure and behavioral characteristics of rats. Furthermore, the rat-like robot can recognize the behavior of rats based on the recognition system during the robot-rat interaction. Additionally, the linear mathematical modeling of the relationship between rat behavior and the stress level of rats is pre-installed in the robotic system. The interaction experiments show that the control of the robot allows creating friendly or agonistic relationship with rats based on the linear model. Likewise, the experiment results prove that the developed system can be applied for multiple mental disorder research, e.g., creating RMMD through agonistic interaction, reducing the degree of mental disorder by decreasing the stress level through friendly interaction.

This research contributes in providing a general solution of analyzing the social interaction in various animal experiments, and then realizing better controllability and reproducibility. This research also represents a significantly important basis and step towards the realization of clarifying the mechanism of mental disorder. Furthermore, this work will bring new insights and reform for the future animal behavior research. Consequently, the robot based

animal experimental system can be applied in many areas, such as psychology, pharmacology, pathology, clinical medical, ecology, etc.

In a short summary, the author achieved to develop an intelligent robotic system:

1) Able to analyze and control the stress level of rats objectively and quantitatively based on the modeled interaction between the robot and rats.

2) Designed with rat-like shape and endowed with the ability to imitate the behavior of rats based on the modeling body structure and behavioral characteristics of rats.

3) High ability to recognize the behavior of rats based on the recognition system.

4) Able to be used for multiple mental disorder research, for instance, creating RMMD through agonistic interaction, reducing the degree of mental disorder by decreasing the stress level through friendly interaction.

Besides, the originality of this thesis is concluded as below.

1) Objective and quantitative analysis of the relationship between rat behavior and the stress level of rats.

2) Novel methodology to create RMMD.

3) Novel methodology to control the psychological status (stress level) of animals.

# 7.2 Future Works

The current system achieves to analyze the stress level of rat quantitatively. However, the relationship between the robot behavior and rat behavior, i.e., $\psi(f_b^3)$ illustrated in　is not determined yet. If $\psi(f_b^3)$ is determined, integrated with $f(f_b^2)$ the relationship between the robot behavior, the rat behavior, and stress level of rats ($\varphi(S, f_b^2)$) can be specified. Consequently, the behavior of the robot can be generated correspondingly to the rat behavior and the stress level of rats quantitatively, bringing significant contribution to the research on realistic psychological and pharmacological applications.

Regarding the analysis of the stress level of rats, only the behavior related parameters are considered currently. Focusing on the realistic application in the pharmacology, the physiological analysis such as, blood pressure, blood sugar levels, brain changes, etc., should be taken into account. In addition, new insights can be found when implementing anatomical analysis on the rat subjects. Therefore, more comprehensive findings can be obtained when
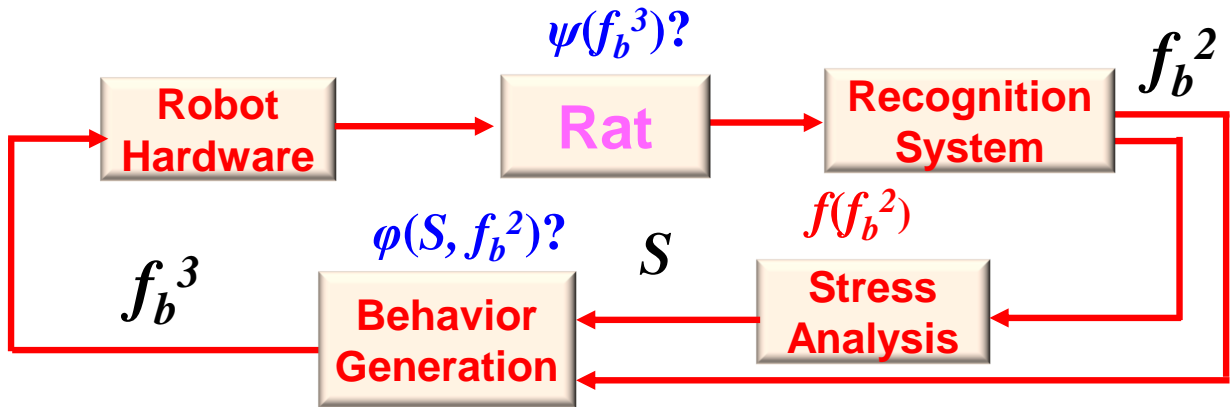
Figure 7.1 The undetermined mathematical models in the robot-rat interaction

collaborating with some pharmacologists involved. In addition, more realistic results may be obtained when considering the effects of smell and sound, as well as the fur. Besides, to improve the generality of results, different experimental conditions should be considered, such as conducting experiments on different weeks of rat subjects, extending the duration of each experiment, putting a robot with multiple rats in the experimental field, differences between male and female subjects, etc.

On the other hand, the author will develop a robot can convey a completely natural impression on living rats. It will be able to mimic more new types and variations of rat behavior. Furthermore, regarding the future rat-like robot, more sensors and optimized control system allow better intelligence.

Finally, the newly-developed superior system will be potentially applied for other researches related to animal behavior research, for example mirror neurons.

# Appendix A

# Rats' Preference to the Robot

As described in Chapter 3, the design of the shape of the robot should be as similar as possible to a real rat. The author has conducted experiments in order to show the importance of shape similarity between the robot and rats. In addition, these experiments are to evaluate the amount of interest that is induced to the rat by the robot.

In the experiments 3 groups of rats (A, B, C) were used. In each of these 3 groups there are three 9-week F344/Jcl [23] rats. The author conducted the experiments in a 700×700 [mm] open-field. A CCD camera is installed above the field to track the robot based on a color marker. The duration of each experiment is 10 minutes. As shown in Figure A.1, for every rat in group A, WR-3 chases the rat in Tm, and subsequently is keeping a state of immobility for Tum. Regarding rat group B, the experiment procedure is just the same as for group A, but WR-3 is replaced by Waseda Mouse No. 8 (WM-8). Compared to WR-3, the shape WM-8 is more different to the body of a real rat as shown in Figure A.2. Each rat in group C, for a period of $T_m$ minutes, is put in the open-field to interact with another rat. During the remaining period $T_{um}$ minutes, one rat is replaced with a stuffed rat. The author conducted the same experiment for a duration of 6 days. Figure A.3 shows the top view of each group of experimental subjects in an open-field.

For each test, while the robot / stuffed rat was not moving (evaluation phase), the author counted the number of rats approaching the robot / stuffed rat ($n_a$). As there were 3 rats in a
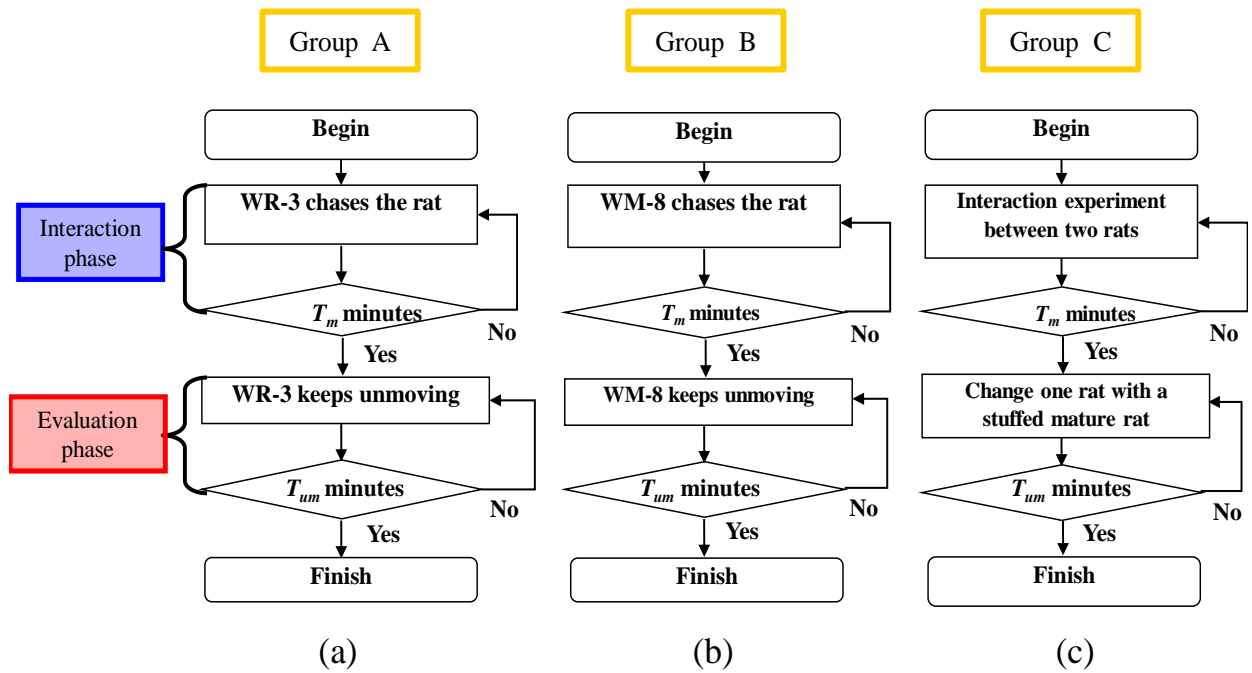
Figure A.1 Evaluation experiment procedures of the rat's interestingness to robots: (a) WR-3 and A group rats; (b) WM-8 and B group rats; (c) Wister rat (stuffed rat) and C group rats.
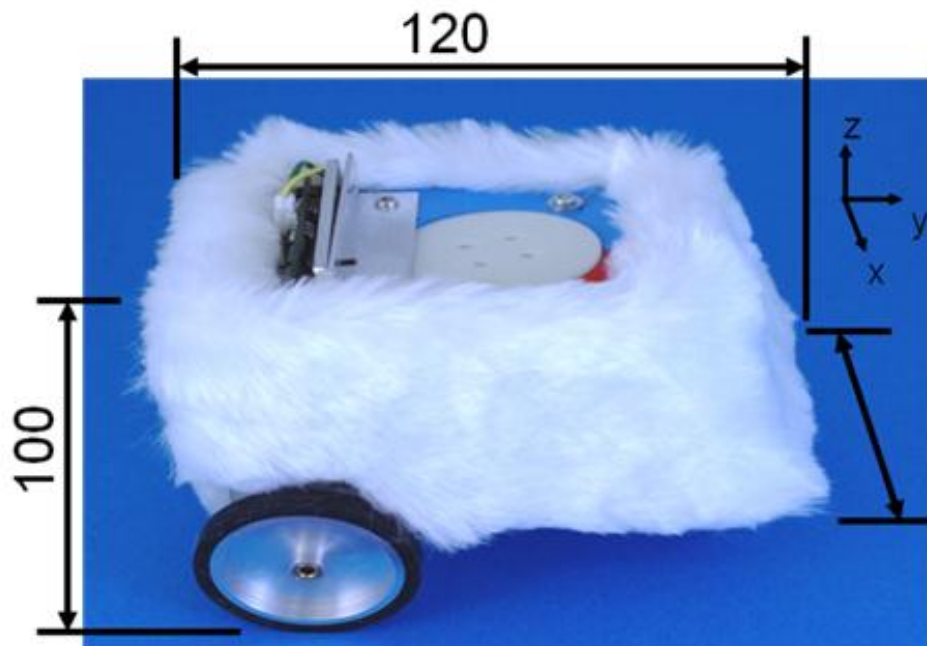


Figure A.2 WM-8: a small mobile robot developed to study mental illness model in 2007.
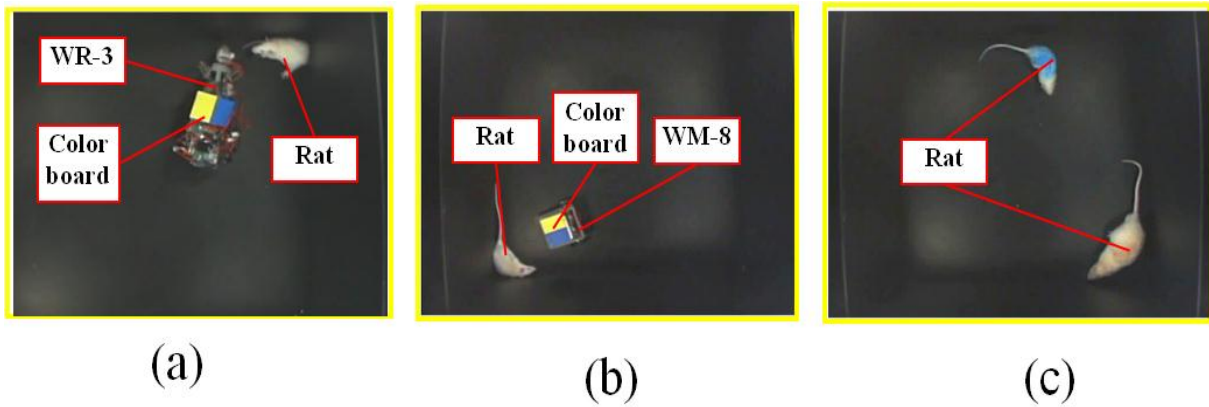
Figure A.3 Evaluation experiment of the rat's interestingness to robots in the $700 \times 700$ [mm] open-field. The color boards in WR-3 and WM-8 are used for image processing.
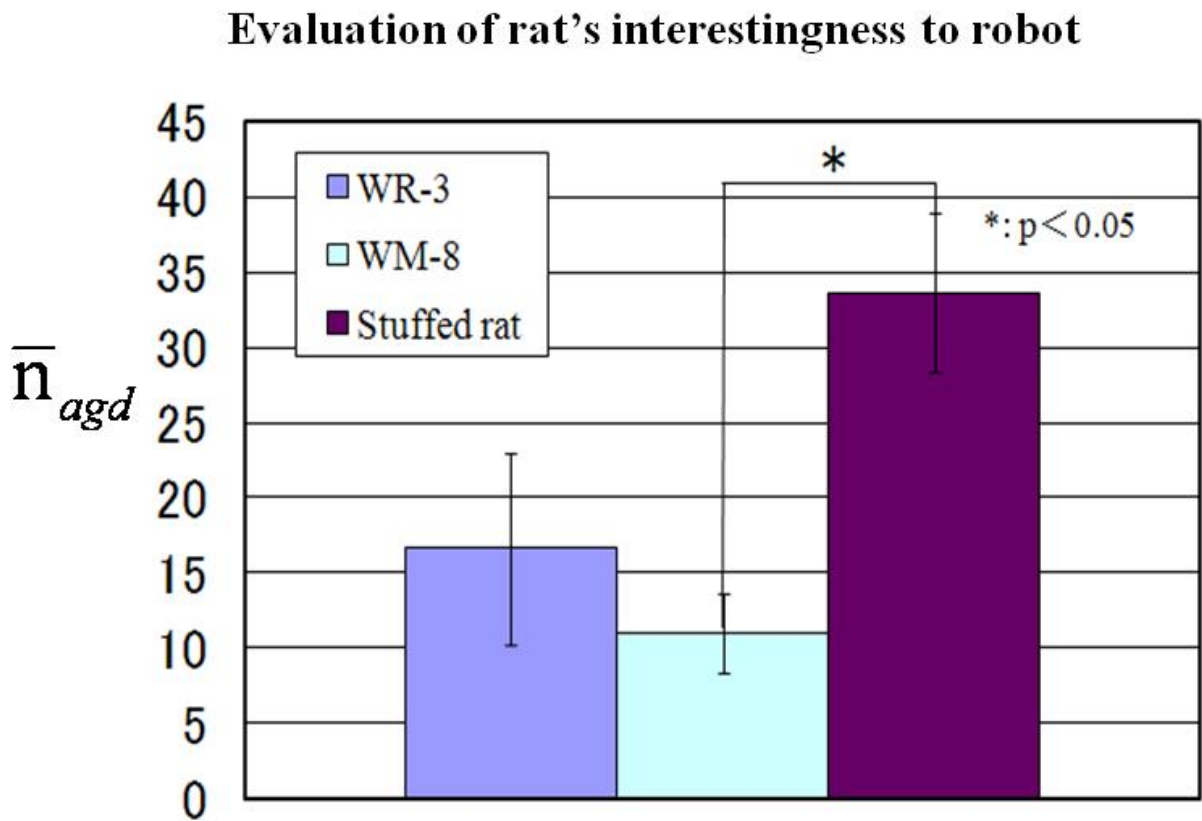


Figure A.4 Evaluation experiment results of the rat's interestingness to robots based on the $\bar{n}_{agd}$ . ($n$: the number of rats)

group and the experiments were conducted for a period of 6 days, the average $n_a$ ($\bar{n}_{agd}$) of each group with respect to days and rat numbers can be derived from Eq. A.1.

$$\bar{n}_{agd} = \frac{\sum_{j=1}^{d}\sum_{i=1}^{n} n_{ai}^{j}}{n \bullet d} \qquad (\text{A.1})$$

Note that $n$ (here $n = 3$) is the number of rats in one group, d the days (here $d = 6$) to do experiments, $n_{ai}$ the number of the $i_{th}$ rat's approaching robot or stuffed rat of one group in an experiment.

Figure A.4 displays the result that in case of the stuffed rat group $\bar{n}_{agd}$ is highest. This shows, that the rats are interested in the objects that have a shape that is similar to them. $\bar{n}_{agd}$ of the WR-3 group is higher than that of the WM-8 group, which shows that WR-3 mimics the shape of the rat better than WM-8. The difference between WR-3 and Stuffed rat group confirms that the body design of WR-3 is still improvable. Although covering WR-3 with a fur and miniaturizing its body size will improve the similarity to a real rat, it also means greater mechanical design complexity.

# Appendix B

# Social Interaction Test between the Robot and Rat

## B.1 WR-3 and Rats

Preliminary social interaction test between WR-3 and living, mature rats has been conducted. The experimental setup is the same as the former experiment described in Appendix A (Figure B.1). Each test has duration of 10 minutes. In the first experiment ($3T_{f1}+T_{f2}$) or $T_{f3}$ minutes, the robot continuously chases the rat. In the remaining $T_{um}$ minutes, the robot stays immobile in the center of the open-field. The amount of total movement of the rat was measured during the interaction phase and the evaluation phase of the robot, as well as the number of rats that approached the unmoving robot.

All rat subjects were devided into 2 groups (A, B), with three 8-week old rats in each group. Every day each of the rats of groups A and B were put into the open-field in order to take a 10-minute experiment with WR-3. The same experiment was conducted continuously for 6 days. In case of group A, when WR-3 rotates to chase the rat, its waist rotates correspondingly. Furthermore, WR-3 performs rearing three times for a period of $3T_{f1}+T_{f2}$ . In case of group B, while WR-3 is chasing the rat, its waist and legs are controlled to remain still,
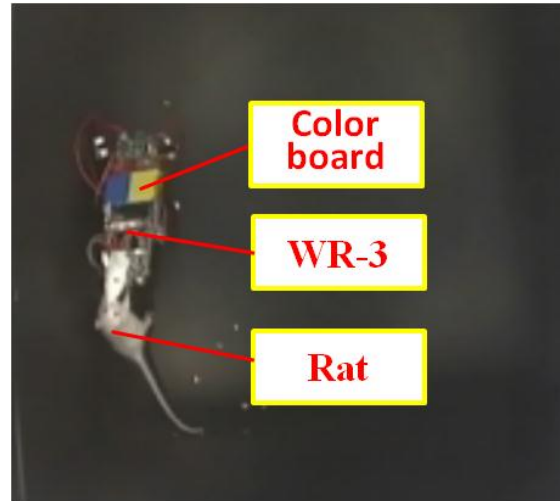
Figure B.1 The social interactions test between the robot WR-3 and a real rat in an open-field. A color board is fixed on the robot for image processing.



(a)　　　　　　　　　　　(b)
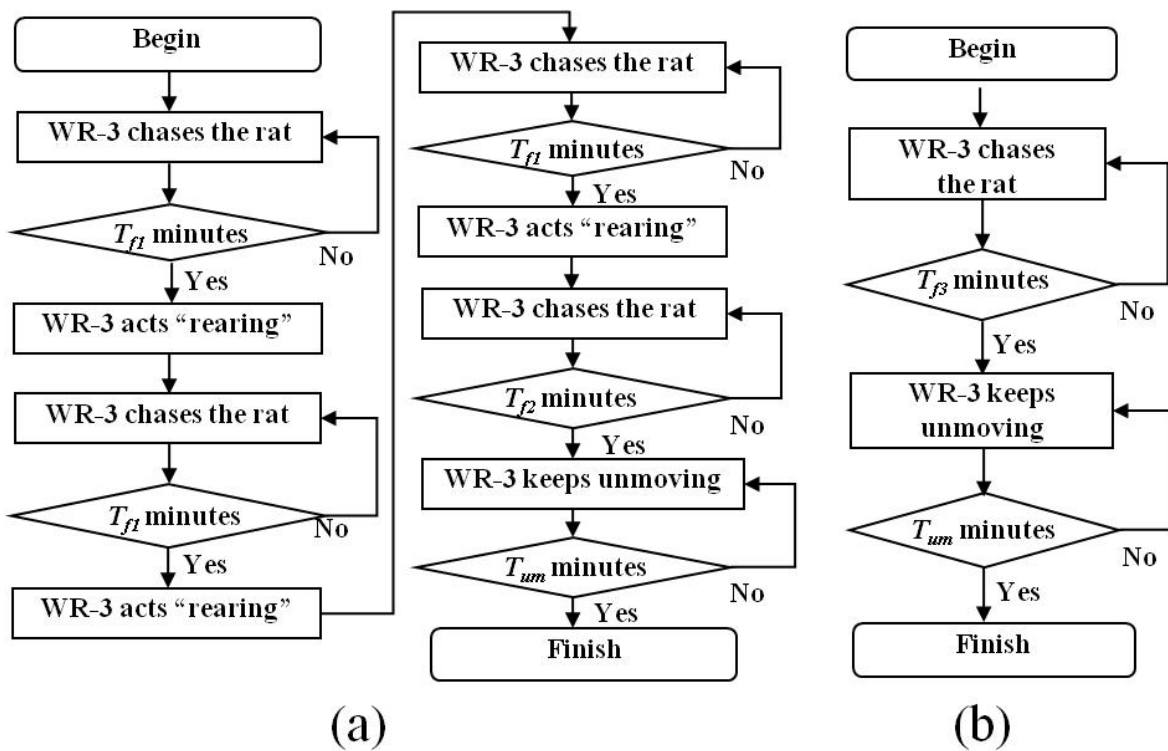
Figure B.2 Social interaction test experimental procedures: (a) Experimental procedures of WR-3 and A group rats; (b) Experimental procedures of WR-3 and B group rats. $T_{f1}$: The first threshold time of robot chasing rat, here it is 2 minutes; $T_{f2}$: The second threshold time of robot chasing rat, here it is 1 minute; $T_{f3}$: The third threshold time of robot chasing rat, here it is 7 minutes; $T_{um}$: Threshold time of robot keeping unmoving, here it is 3 minutes.
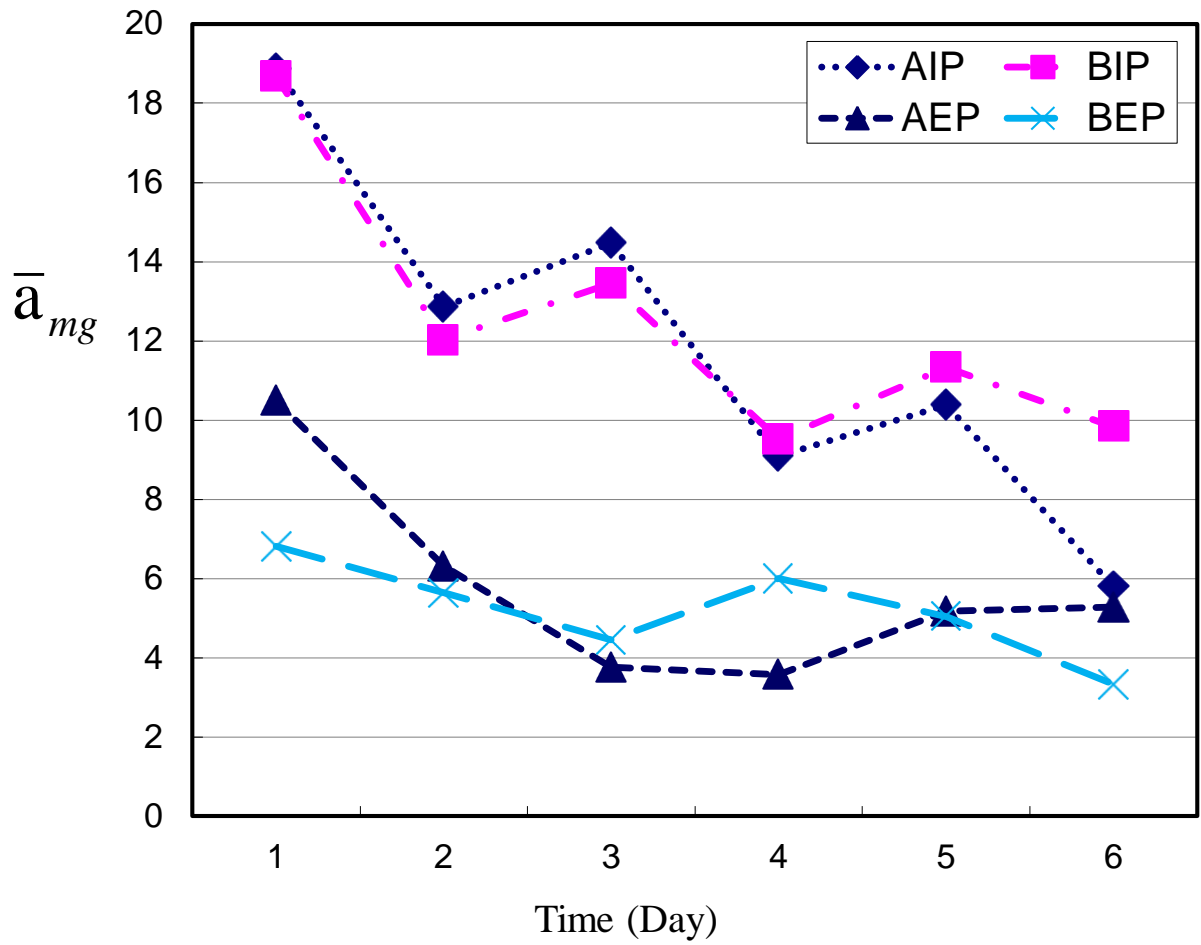
Figure B.3 Social interaction test results of $\bar{a}_{mg}$. Note that the number of rats in each group is 3, AIP: A group rats in interaction phase, BIP: B group rats in interaction phase, AEP: A group rats in evaluation phase, BEP: B group rats in evaluation phase.

and therefore not perform any social actions, except following (chasing) the rat. The details of the experiment procedures of each group are shown in Figure B.2.

Using image processing, the amount of total movements ($a_m$) of a rat can be obtained for each day the experiment was performed. As there are 3 rats in each group, so it is able to calculate $\bar{a}_{mg}$ (average of $a_m$) for each group with the following equation.
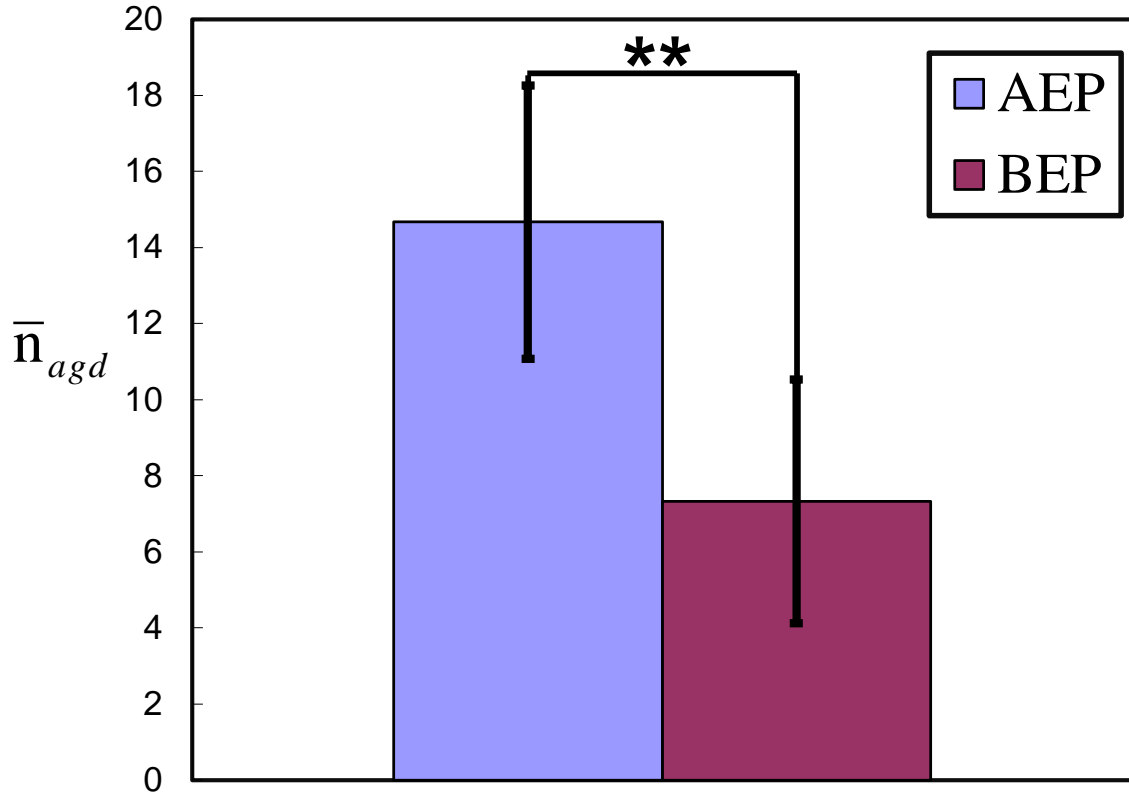
Figure B.4 Social interaction test results of $\bar{n}_{agd}$ measured in evaluation phase. AEP: A group rats in evaluation phase, BEP: B group rats in evaluation phase. Student's t-test ($n = 6$; **: $p < 0.01$);

$$\bar{a}_{mg} = \frac{\sum_{i=1}^{n} a_{mi}}{n} \qquad (B.1)$$

In Eq. B.1 $n$ (here $n = 3$) is the number of rats in a group, $a_{mi}$ the number of approaches to the robot of the $i$th rat. The results in Figure B.3 (a) show, that both $\bar{a}_{mgA}$ ($\bar{a}_{mg}$ of group A) and $\bar{a}_{mgB}$ ($\bar{a}_{mg}$ of group B) decrease gradually. That suggests the idea that rats were getting used to the robot, resulting from the continuous interaction experiments performed every day. It shows that the trend of $\bar{a}_{mgA}$ and $\bar{a}_{mgB}$ in relation to days are quite similar in every phase as well. The author calculated $\bar{n}_{agd}$ of groups A and B as shown in Eq. 4. Figure B.3 (b) demonstrates that

$\bar{n}_{agdA}(\bar{n}_{agd}$ of group A) is significantly larger than $\bar{n}_{agdB}(\bar{n}_{agd}$ of group B) during the immobility phase of the robot. Therefore, in the experiments with rats of group A, we considered that the rats' movements vary with the result of the rotating, rearing and waving actions of the robot. In the test, the author found that when WR-3 is rearing, occasionally the rat performs rearing correspondingly. This phenomenon reveals that if the robot does a certain social action, the rat may actively do corresponding social actions to imitate the robot. Therefore the author argues that the robot WR-3 is successfully able to inspire actions of a rat to some extent.

# B.2 WR-4 and Rats

Experiments on [91] revealed that if the robot acts certain social behavior, the rat may actively imitate the robot. To definitely prove this discovery, the specific social behavior of rats should be selected as the test item. Firstly the author is focusing on observing the rearing behavior of rats, which is considered as one of the most general social behaviors by the animal psychologists. SIT between WR-4 and living, mature rats was conducted in a 700×700 [mm] open-field [105] as shown in Figure B.5. A CCD camera is installed above the field to track the white rats and the robot covered by a color marker. Each test has duration of 10 minutes. As shown in Figure B.6, in the first experiment Tm minutes, the robot continuously chases the rat. In the remaining Tim minutes, the robot stays immobile in the center of the open-field. The author measured the frequency of rearing behavior (achieved by the system proposed in [108]) in rats during the interaction phase, as well as the amount of movement and the frequency of approaching the robot in rats (achieved by the system proposed in [105]) during the evaluation phase. The latter two parameters (the amount of movement and the frequency of approaching the robot in rats) integrated together, are considered as the activity index of rats, and are quite important for psychological analysis. Thus these parameters involved in activity of the rat need to be measured as well.

All rat subjects used in the experiment were divided into 2 groups (A, B), with six 9-week old F344/Jcl rats in each group. Every day each rat of group A and B was put into the open-field to take a 10-minute experiment with WR-4. The same experiment was continuously conducted for 6 days. The rats of group A were exposed to WR-4 that is only keeping on chasing the rat. In case of group B, WR-4 chased the rat and acted rearing 4 times, and the
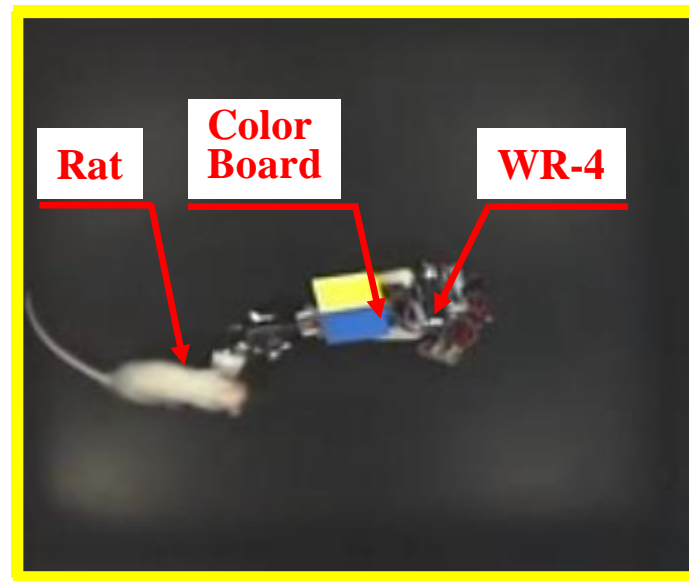
Figure B.5 The SIT is conducted between WR-4 and living, mature rats in an open-field.
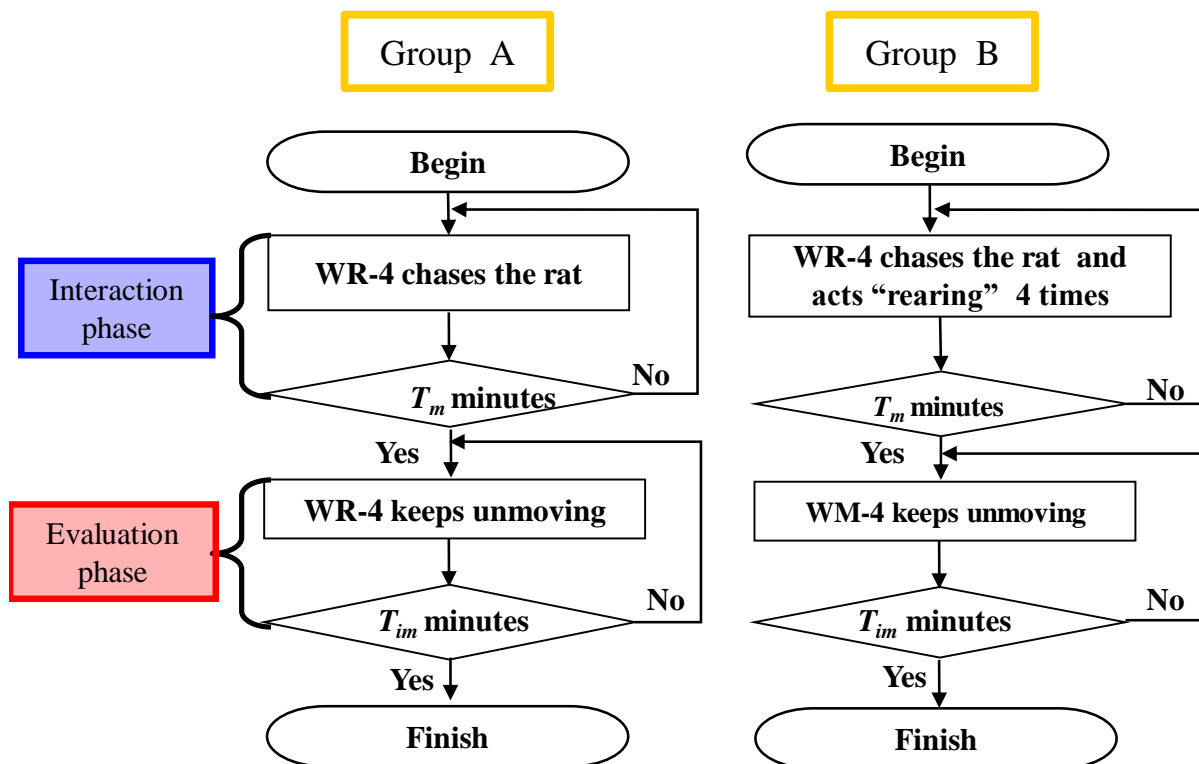


Figure B.6 SIT experimental procedures of WR-4 with the rats of A and B group. $T_m$: Threshold time of robot chasing rat, here it is 7; $T_{um}$: Threshold time of robot keeping unmoving, here it is 3.

time point to act rearing was the 1st, 3rd, 5th, 7th minute of one experimental duration.

The evaluation parameters in each rat were scored in each test, that is the frequency of rearing behavior $f_r$, amount of movement $a_m$, and frequency of approaching robot $f_a$. As the mean value of each parameter is calculated with respect to experimental rat numbers n and experimental days $d$, the author can substitute $x$ as any one of $f_r$, $a_m$ and $f_a$. Given $n = 6$, $d = 6$, the mean of $x$ ($\bar{x}$) can be derived as following. The mean value of each parameter can be calculated based on this equation.

$$\bar{x} = \frac{\sum_{j=1}^{d} \sum_{i=1}^{n} x_i^{j}}{n \cdot d} \tag{B.2}$$

Note that $x_{ji}$ means the parameter value of the $i$th rat of A/B group in the $j$th day. The left of Figure B.7 shows mean frequencies of rearing behavior in rats of group A and B. It demonstrates that the frequency of rearing behavior in rats of group B was significantly larger than that of group A during the interaction phase. Therefore, in the experiments with rats of group B, it can be assumed that the frequency of rearing behavior in rats varied with the rearing behavior of the robot. Furthermore, as shown in the right of Figure B.7, although a drop appeared at the 3rd day, rearing behavior was increased gradually in rats of group B and with a peak at the 6th day. However, rearing behavior showed no significant change in rats of group A exposed to the robot that did not act rearing behavior. This suggests that the elevated level of rearing behavior observed in rats of group B most probably was induced by the robot that periodically acted rearing. Consequently, the author argues that the robot WR-4 is successfully able to inspire rearing behavior of rats to some extent, partly confirming the discovery described in [91].

Figure B.8 shows that both the amount of movement and frequency of approaching robot in rats of group A were significantly larger than that of group B during evaluation phase. The declined activity level in rats of group B may be one of the psychological reactions to the rearing behavior of the robot. It seems that the activity of rats was decreased after the robot acted rearing behavior.
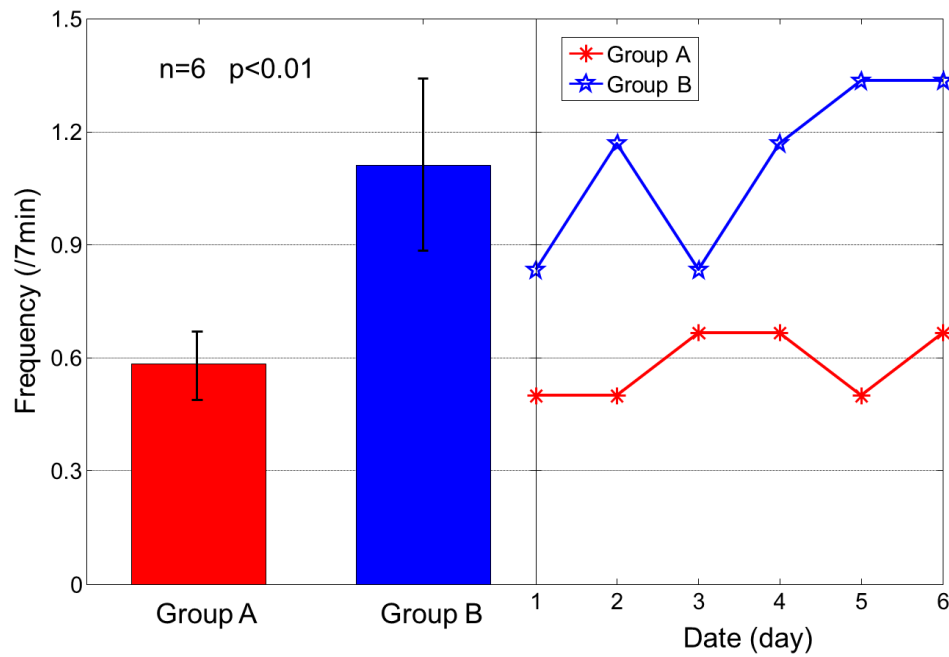
Figure B.7 Mean frequency of rearing behavior in rats with respect to days and experimental rat numbers (left). Mean frequency of rearing behavior in rats with respect to experimental rat numbers (right).
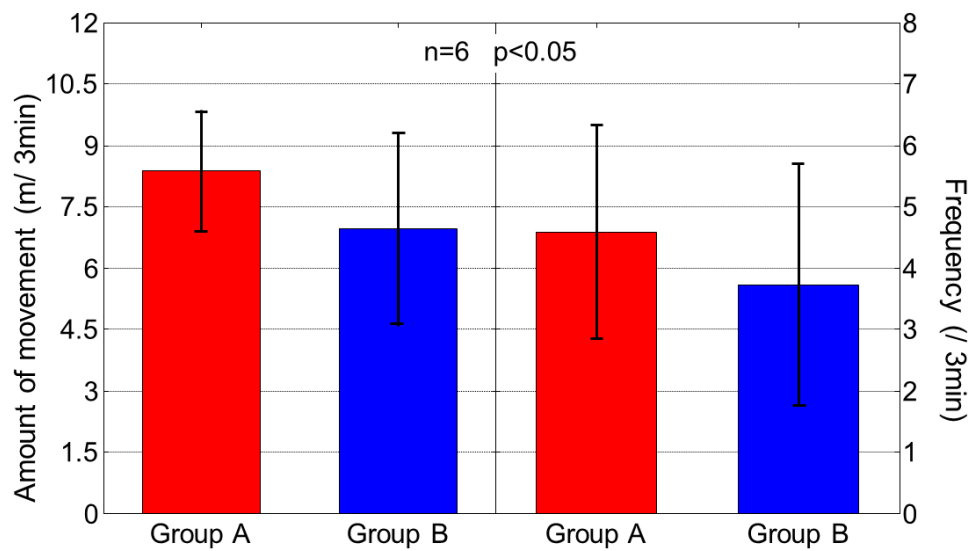


Figure B.8 Mean amount of movement (left), and mean frequency of approaching the robot (right) in rats with respect to days and experimental rat numbers.

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# Research Achievements

| 種類別 | 題名 | 発表・発行掲載誌名 | 発表・発行年月 | 連名者 |
|---|---|---|---|---|
| 1. 論文 | A Rat-like Robot for Interacting with Real Rats | Advanced Robotics | 2012 年 (submitted) | **Qing Shi**, Hiroyuki Ishii, Shinichi Kinoshita, Shinichiro Konno, Atsuo Takanishi, Satoshi Okabayashi, Naritoshi Iida, Hiroshi Kimura |
| | A Robot-rat Interaction Experimental System based on the Rat-inspired Mobile Robot WR-4 | 2011 IEEE International Conference on Robotics and Biomimetics (ROBIO2011), pp.402-407. | 2011 年 12 月 (published) | **Qing Shi**, Hiroyuki Ishii, Shinichiro Konno, Shinichi Kinoshita, Atsuo Takanish, Satoshi Okabayashi, Naritoshi Iida, Hiroshi Kimura |
| | Development of a Hybrid Wheel-legged Mobile Robot WR-3 Designed for the Behavior Analysis of Rats | Advanced Robotics,Vol.25,No.18 , pp.2255-2272. | 2011 年 12 月 (published) | **Qing Shi**, Hiroyuki Ishii, Shunsyuke Miyagishima, Shinichiro Konno, Syogo Fumino, Atsuo Takanish, Satoshi Okabayashi, Naritoshi Iida, Hiroshi Kimura |
| | Development of a Cognition System for Analysis of Rat's Behaviors | 2010 IEEE International Conference on Robotics and Biomimetics (ROBIO2010), pp.1399-1404. | 2010 年 12 月 (published) | **Qing Shi**, Shunsyuke Miyagishima, Syogo Fumino, Shinichiro Konno, Hiroyuki Ishii, Atsuo Takanish |
| | Development of a Novel Quadruped Mobile Robot for Behavior Analysis of Rats | 2010 IEEE International Conference on Intelligent Robots and Systems (IROS2010), pp.3073-3078. | 2010 年 10 月 (published) | **Qing Shi**, Shunsyuke Miyagishima, Syogo Fumino, Hiroyuki Ishii, Atsuo Takanish, Celilia Laschi, Barbara Mazzolai, Virgilio Mattoli, Paolo Dario |

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|---|---|---|---|---|
| 論文の続き | Development of Experimental Setup to Create Novel Mental Disorder Model Rats Using Small Mobile Robot | 2010 IEEE International Conference on Intelligent Robots and Systems (IROS2010), pp.3905-3910. | 2010 年 10 月 (published) | Hiroyuki Ishii, **Qing Shi**, Atsuo Takanish, Satoshi Okabayashi, Naritoshi Iida, Hiroshi Kimura, Yu Tahara, Akiko Hirao, Shigenobu Shibata |
| | Development of the Hybrid Wheel-legged Mobile Robot WR-3 Designed to Interact with Rats | 2010 IEEE International Conference on Biomedical Robotics and Biomechatronics (BioRob2010), pp.876-881. | 2010 年 9 月 (published) | **Qing Shi**, Shunsyuke Miyagishima, Shinichiro Konno, Syogo Fumino, Hiroyuki Ishii, Atsuo Takanish, Celilia Laschi, Barbara Mazzolai, Virgilio Mattoli, Paolo Dario |
| | Design and Development of Bio-mimetic Quadruped Robot | Proceedings of the 18th CISM-IFToMM Symposium on Robot Design, Dynamics, and Control (RoManSy2010), pp.257-264 | 2010 年 7 月 (published) | Hiroyuki Ishii, **Qing Shi**, Yuichi Masuda, Syunsuke Miyagishima, Syogo Fumino, Atsuo Takanish, Satoshi Okabayashi, Naritoshi Iida, Hiroshi Kimura |
| 2. 講演 | Study on the Development of an Intelligent Animaloid to Analyze and Control the Stress Level of Rats | International Workshop on Micro-nano Mechatronics for the Interaction of Young Researchers | 2011 年 11 月 | **Qing Shi**, Hiroyuki Ishii, Shinichiro Konno, Shinichi Kinoshita, Atsuo Takanish, Satoshi Okabayashi, Naritoshi Iida, Hiroshi Kimura |

| 種類別 | 題名 | 発表・発行掲載誌名 | 発表・発行年月 | 連名者 |
|---|---|---|---|---|
| 講演の続き | 小型移動ロボットを用いた精神疾患モデル動物の開発-ロボットとの相互作用を通したストレス暴露法- | 第 29 回日本ロボット学会学術講演会予稿集 | 2011 年 9 月 | 石井裕之,<br>**石青**,<br>文野翔吾,<br>今野紳一朗,<br>木下新一,<br>岡林誠士,<br>飯田成敏,<br>木村裕,<br>田原優,<br>柴田重信,<br>高西淳夫 |
| | 小型移動ロボットを用いたラットの社会性評価のための新たな実験系の構築第 5 報: 多段屈曲可能な体幹を有するラット形アニマロイドの開発 | 第 29 回日本ロボット学会学術講演会予稿集 | 2011 年 9 月 | 木下新一,<br>文野翔吾,<br>**石青**,<br>今野紳一朗,<br>石井裕之,<br>高西淳夫,<br>飯田成敏,<br>木村裕,<br>岡林誠士 |
| | ロボットとの相互作用による精神疾患モデル動物（ラット）作成手法の提案 | 日本動物心理学会（第 71 回） | 2011 年 9 月 | 石井裕之,<br>**石青**,<br>文野翔吾,<br>今野紳一朗,<br>木下新一,<br>高西淳夫,<br>岡林誠士,<br>飯田成敏,<br>木村裕,<br>柴田重信 |
| | Development of a Cognition System for Recognition and Analysis of Rat's Behaviors | the 28th Annual Conference on the Robotics Society of Japan | 2010 年 9 月 | **Qing Shi**,<br>Shunsyuke Miyagishima,<br>Syogo Fumino,<br>Hiroyuki Ishii,<br>Atsuo Takanish |

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|---|---|---|---|---|
| 講演の続き | 小型移動ロボットを用いた精神疾患モデル動物の開発-精神疾患脆弱性仮説の検証- | 第 28 回日本ロボット学会学術講演会予稿集 | 2010 年 9 月 | 石井裕之,<br>**石青**,<br>宮城島俊介,<br>文野翔吾,<br>今野伸一郎,<br>高西淳夫,<br>岡林誠士,<br>飯田成敏,<br>木村裕,<br>田原優,<br>平尾彰子,<br>柴田重信 |
| | Development of a Novel Quadruped Mobile Robot For Social Interaction Test with Rats | NTU-WASEDA Student Workshop 2009 in Bioscience and Biomedical Engineering | 2009 年 12 月 | **Qing Shi**,<br>Shunsyuke Miyagishima,<br>Syogo Fumino,<br>Hiroyuki Ishii,<br>Atsuo Takanishi |
| | Development of Quadruped Robots for Social Interaction Test with Rats | International Cross-disciplinary Symposium on Micro-Nano System | 2009 年 11 月 | **Qing Shi**,<br>Hiroyuki Ishii,<br>Shunsyuke Miyagishima,<br>Syogo Fumino,<br>Atsuo Takanishi |
| 3. その他 (賞) | Silver Award Winner for Best Poster | WSK-TNg Summer School 2010 | 2010 年 10 月 | **Qing Shi** |