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A rat-like robot for interacting with real rats

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SUMMARY
We developed a novel small rat-like robot called Waseda Rat No. 4 (WR-4) to interact with real rats. WR-4 can perform both rearing (rising up on its hind limbs) and rotating (body bending during movement) actions faster than live mature rats. After robot–rat interaction involving rearing and body grooming (body cuddling and head curling) actions of WR-4, real rats showed more activity and greater interest in the robot. Similar results evident from rat–rat interaction suggest that a rat-like robot is able to interact with rats in the same way as real rats. Furthermore, lower variances between the rat subjects in robot–rat interaction reveals that a rat-like robot can more effectively impact rat's behavior in a controllable, predictable way.

KEYWORDS: Rat-like, WR-4, Robot–rat interaction, Biomimetic robots, Design, Mobile robots.

1. Introduction

The study of animal behavior has a long history covering many fields, and has significantly influenced progress in subjects such as neuroscience, psychology, and pharmacology. For example, operant conditioning, which is one of the most important theories in psychology about learning, was established through an experiment with rats by Skinner.[1] In the study of animal behavior, social interactions between individuals have drawn much interest for a range of completely different purposes. One of the most notable purposes is to screen psychotropic drugs and clarify the mechanism of mental disorder by creating animal models of mental disorders (AMMDs). This is particularly relevant when treating a constantly increasing number of patients suffering from mental disorders induced mainly by social stress.[2] Animal models are living experimental systems used to analyze brain-behavior relationships under controlled conditions, and are used to represent phenotypes, such as behavioral disorders or plastic changes in the brains of human patients suffering from mental disorders. In general, rats or mice are used for modeling such mental disorders because of their genetic consistency and similarity with human beings in their reaction to drugs. Recently, rats or mice have been used as candidates in screening test of psychotropic drugs. In these tests, newly developed psychotropic drug is administrated to a candidate, and then clinical effects of the candidate are estimated based on observation of its behavioral changes.[3] Rat or mouse models hold an important role in helping us understand the complex inter-relationship between mental disorder and physical activity.[4] They are created by genetic manipulation, surgical operations on the brain, psychotropic drugs, or stressful environments.[5,6] Although ignored in conventional animal experiments, environmental factors contribute greatly to the development of rat models of mental

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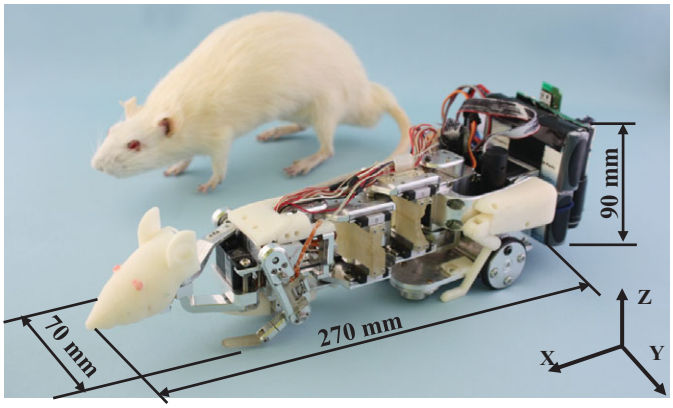


Fig. 1. (Colour online) Shapes of the mobile robot WR-4 and a stuffed mature rat.

disorders (RMMDs), which can be created by exposing rats to agonistic partners in an interaction process.[7]

In addition, the extent of sociality and anxiety in RMMDs is evaluated through several behavioral tests, such as social interaction,[8,9] forced swimming,[10] conflict,[11] and open-field[12] tests. With regard to the symptoms of mental disorder in humans, the social interaction is considered one of the main indices.[9] Therefore, we focus on social interactions between two subjects involved with a level of anxiety. During social interaction test, the amount of movement, frequencies of actions (for instance, *rearing*: rising up on its hind limbs and *body grooming*: body cuddling and head curling, considered similar to *rotating*: body bending during movement), and mutual preference (for instance, approaching frequency and rat–rat distance) are measured to evaluate the sociality and anxiety of rats. As confirmed in our previous research, a rat that exhibits lower activity (less amount of movement, fewer frequencies of actions, etc.) has a higher level of anxiety than a normal rat.[7] There are many types of social interactions between rats, such as being agonistic, friendly, or neutral. In particular, agonistic interaction is conducted to create RMMDs as introduced in Ishii *et al*. (2010).[7]

However, interaction experiments between live animals are not adequately reproducible because of individual differences. Furthermore, live animals are almost uncontrollable and immeasurable. The bio-inspired robots may help because of their programmability and reconfigurability when testing different models. In fact, the robot offers two distinct advantages against live animals in such studies.[13] As a novel approach, we propose an experimental system in which we replace a real rat by a bio-inspired robot to perform interactions with another rat. As a requirement for successful experiments, the shape and movement capabilities of the robot should be designed similar to a live mature rat. As a short-term objective, we aim to design a rat-like mobile robot that has a shape similar to a real mature 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 a developed rat-like robot to analyze the behavior of RMMDs in realistic psychological and pharmacological applications for screening psychotropic drugs and clarifying the mechanism of mental disorder. In this research, building on the experiences gained from previous robot prototypes, we developed an improved rat-like robot called WR-4 as shown in Fig. 1. WR-4 can perform both rearing and rotating actions faster than live mature rats. After robot–rat interaction involving rearing and body grooming actions of WR-4, real rats become more active and show greater interest in the robot. Similar results can be obtained from rat–rat interaction, suggesting that a rat-like robot is able to interact with rats in the same way as real rats. Furthermore, lower variances between the rat subjects in robot–rat interaction reveals that a rat-like robot can impact a rat's behavior in a controllable, predictable way.

2. Related Work

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

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animal behavior and test beds for the study and evaluation of biological algorithms for potential engineering applications.[13,14] Furthermore, robots are not virtual, but physical entities, and as such they interact with a real environment. This quality, which no simulation or mathematical model has, allows their integration in experiments with real animals.[15] However, the application of biorobotics is restricted to motion performance and intelligence. In an attempt to fully use the advantages of biorobotics, many types of robots have been developed recently. For instance, the InsBot robot[16] can discriminate cockroaches, other robots, environment boundaries, and shelters. It has three means of communication for monitoring, logging, and supervision of biological experiments, and detecting other robots within a short range. In Landgraf *et al.*[17], the authors introduced a honeybee robot capable of reproducing very realistic dances and reacts with its environment. This robot promises to enable biologists to conduct complex biological experiments on the honeybee dance communication system. Gribovskiy *et al.*[18] developed a chicken robot called PoulBot, which is able to autonomously record experimental video and audio data to detect the displacement of chicks and robots, to detect their calling activity, and to provide the robot with these data. The robot can be accepted by chick groups using the filial imprinting learning process modulated by the patterns displayed and the sounds emitted by the robot. Similarly, it serves to quantify both individual and group behavior and to study the impact of the individual behavioral parameters at a collective level. The Psikharpax project in France[19] aims at designing an artificial rat able to survive in a laboratory populated with humans and other robots. In particular, the studies described in Asadpour *et al.*[16] and Gribovskiy *et al.*[18] are quite similar to our project, which aims to interact with the real world of animals. However, InsBot and PoulBot do not resemble real live creatures in external appearance, something which is significantly important for our own research as confirmed in Shi *et al.*[20]

In our previous research, several rat-like mobile robots have been developed to study rat behavior.[20–22] In Ishii *et al.* (2009b),[21] a robot called WR-1, similar in its appearance to a mature rat, was proposed. Although WR-1 was capable of expressing actions such as rearing and rotating, it was significantly larger than a mature rat and could only move at a low speed ($v_{\text{maxWR-1}} = 0.02$ m/s) while walking. Ishii *et al.* (2009b)[22] describe a quadruped walking robot called WR-2 that was designed to be similar in size to a mature rat. This robot moved at a very low speed ($v_{\text{maxWR-2}} = 0.03$ 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 stated research hypotheses. As an improvement, we developed a wheel–legged robot called WR-3, which was endowed with higher moving speeds and better imitation behavior[20] by integrating the advantages of wheeled and legged mechanisms. However, experimental results showed that the limited movement range of waist and neck of WR-3 caused a linear bend posture, which was different to the curved bend posture of rats. On occasion the locomotion of WR-3 was unstable. Given this lack of a suitable experimental biomimetic robot platform, we considered that it was essential to develop a robot that could sufficiently imitate rat behavior during an interaction process.

3. System Design

The robot system mainly consists of two parts: mechanical and electrical. The mechanical design is performed based on the behavior modeling of rats, and the electrical part (control board) is the same as the one used in the WR-3 robot. Consequently, this section focuses on the mechanical design.

3.1. Modeling and design concepts

The most important performance characteristic of this robot lies in the imitation of behavior of live rats. To better meet this requirement, a robot skeleton was constructed on the basis of the behavioral model of rats as shown in Fig. 2. Apart from limbs, the social behavior of a rat is mainly implemented by its neck and waist. In view of the limits to its movement, if a robot can perform rearing and rotating actions, the social behavior of *mounting* (one rat placing its forequarters on another rat's rump from behind, considered similar to rearing) and body grooming (considered similar to rotating) will be physically feasible. The movement limits for the rearing angle θ_{wr} (note that the sign of θ_{wr} is opposite to that of pitch) in the x–z plane and the bending angle θ_{wb} in the x–y plane are determined in advance as defined in Fig. 2 (the maximum of θ_{wr} and θ_{wb} are approximately 70° and 110° respectively). These two parameters are used as key references for joint design and actuator selection.

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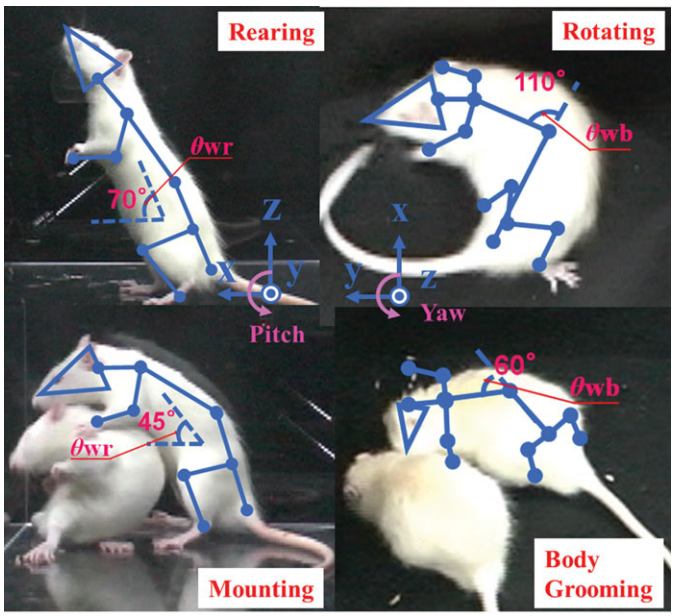


Fig. 2. (Colour online) The behavioral model of rats. The maximum values of θ_{wr} and θ_{wb} correspond to the movement limits for rearing and rotating actions. Taking into account the movement limits, mounting and body grooming actions are quite similar to rearing and rotating actions.

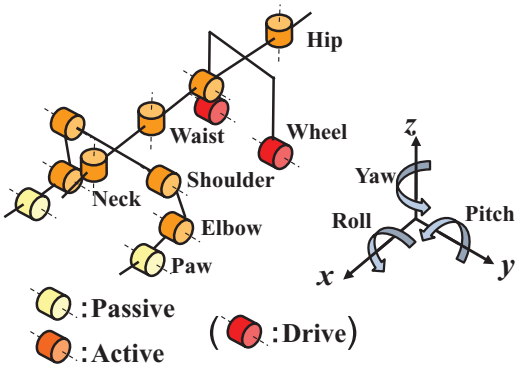


Fig. 3. (Colour online) DOF arrangement of WR-4 is determined by the behavioral model, anatomy pictures, and motion analysis of rats. Two wheels configured for 1 DOF are for locomotion, and the other 8 active DOFs are integrated together to mimic rat behavior.

Based on the observation of rat actions, their motion can be roughly divided into two phases: movement and interaction. To better mimic rat actions we proposed a hybrid-driven mechanism: wheel–legged mechanism. In the movement phase, a wheeled mechanism composed of two wheels, exerts considerable force and torque enabling it to drive a robot to catch up with a rat in a short space of time. After moving near the rat, the forelegs driven by a legged mechanism, and the waist and neck move together to allow the robot to dexterously interact with the rat. Furthermore, inspired by rat anatomy pictures,[23] we evolved the skeleton structure of WR-4 as represented by the degree of freedom (DOF) arrangement depicted in Fig. 3. WR-4 consists of 10 active DOFs (two 1-DOF wheels for locomotion, two 2-DOF forelegs for interaction, one 1-DOF neck for swing, one 2-DOF waist for performing rearing and body grooming actions, and one 1-DOF reserved for the tail) and two passive DOFs in the paws.

3.2. Mechanical design

The waist, foreleg, and neck of WR-4 have changed significantly to address the shortcomings of WR-3. Thus, the mechanical design of WR-4 focused on these three parts.

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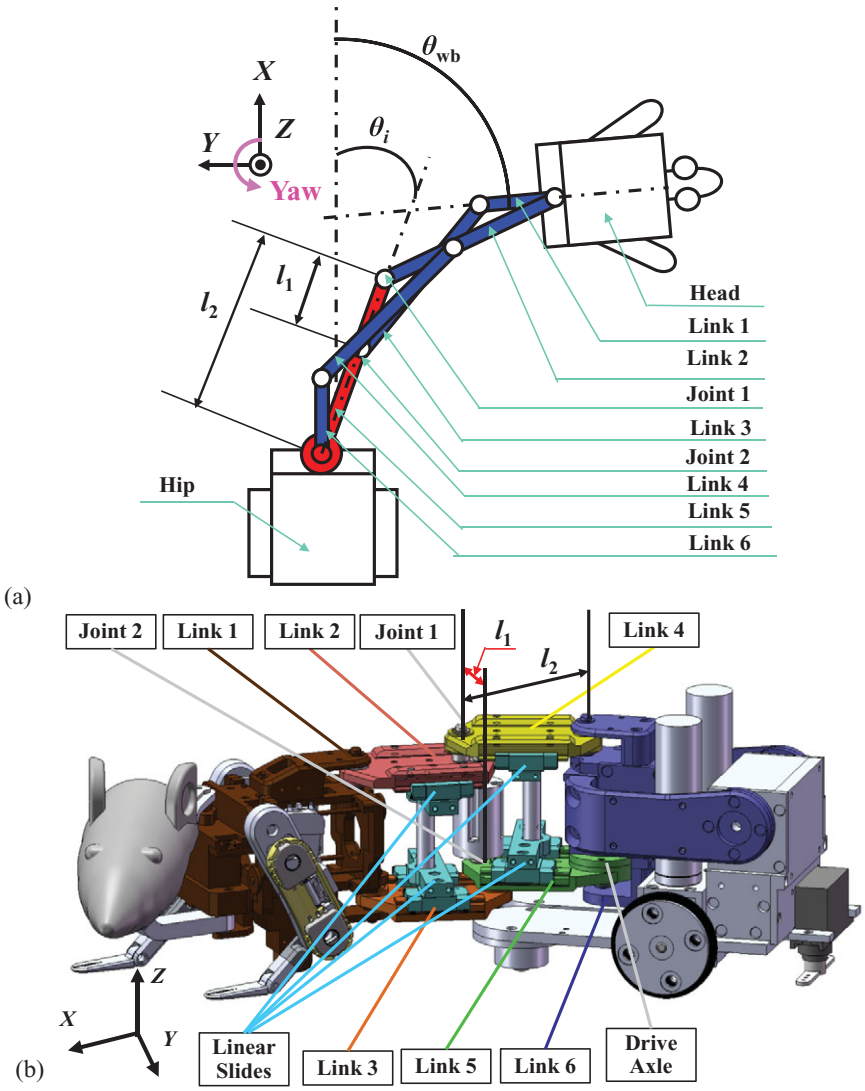


Fig. 4. (Colour online) The waist of WR-4 is equipped with a multi-bendable six-bar linkage mechanism. (a) The Geometric characteristic between θ_i and θ_{wb}; (b) The mechanical design view of WR-4.

3.2.1. Waist. The waist of WR-4 configured with two DOFs is actuated by servo motors: one DOF around the pitch axis serves to drive rearing action, the other around the yaw axis serves as a drive axle for the multi-bendable six-bar linkage mechanism as illustrated in Fig. 4. Based on the mechanical geometry and design view of the waist as shown in Fig. 4, the mathematical relationship between waist bending angle θ_{wb} around the yaw axis and output angle of servo motor (rotation angle of drive axle θ_i) can be derived by the following two equations:

$$e = \frac{l_1}{l_2}, \tag{1}$$

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

Note that l_i is the length of the ith link: $l_1 = l_6 = 5$ mm, $l_2 = l_3 = l_4 = l_5 = 35$ mm. The distance between joints 1 and 2 is: $d_{j12} = l_1 = 5$ mm. As the output angle range of drive axle is $-45^\circ \leq \theta_i \leq 45^\circ$, the range of waist bending angle is calculated as $-130^\circ \leq \theta_{wb} \leq 130^\circ$.

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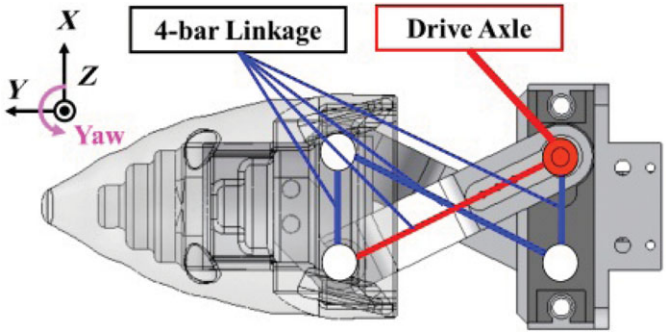


Fig. 5. (Colour online) Mechanical design of the neck. The four-bar linkage mechanism in the neck enables WR-4 to mimic the bent neck posture of rats.

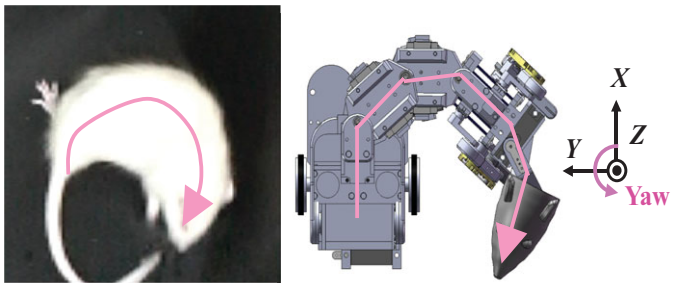


Fig. 6. (Colour online) The bent waist and neck posture comparison between rat and WR-4. WR-4 has the flexibility to fully emulate the curved posture of live rats.

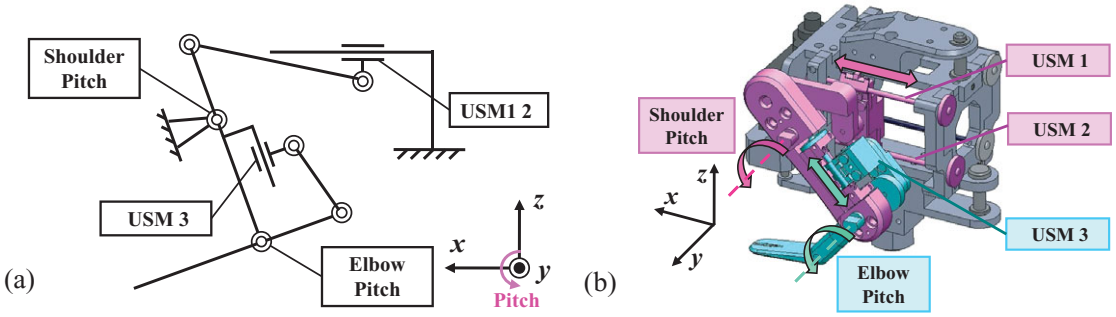


Fig. 7. (Colour online) (a) Mechanism principle, and (b) mechanical design of the left foreleg.

As shown in Fig. 4(b), there are four linear slides that are used for the links 2, 3, 4, and 5. The two linear slides used for links 2 and 3 are connected by a shaft with bearing, as are the two linear slides used for links 4 and 5. In general, links 2 and 3 as well as links 4 and 5 cross each other. The role of these linear slides is to avoid any singular point, which easily occurs when all the links remain parallel, in other words when $\theta_i = 0$. Therefore, the six-bar linkage mechanism in waist allows WR-4 to bend in both left and right directions.

3.2.2. Neck. One DOF in the yaw axis is arranged to achieve neck rotation driven by one easily controlled servomotor. As shown in Fig. 5, the adoption of a four-bar linkage mechanism in the neck enables WR-4 to mimic the curved posture of rats when bending the neck. The upper body of WR-4, integrating with the neck and the multi-bendable waist described in the preceding section, guarantees better imitation of the rotating action of rats. As shown in Fig. 6, the waist and neck of WR-4 are able to bend in a curved posture, better simulating the rotating action of rats.

3.2.3. Foreleg. Figure 7 shows the theory of the mechanism and mechanical design of left foreleg (right foreleg is symmetrically similar to the left foreleg). Actions of two forelegs are achieved by

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using a slider crank mechanism driven by an ultrasonic motor (USM). As shown in Fig. 7(b), to guarantee enough power, two motors, USM 1 and USM 2, placed parallel to each other in the body, drive the left shoulder joint to rotate around the pitch axis. USM 3 placed in the upper arm drives the left elbow joint to rotate around the pitch axis. The adoption of USMs significantly contributes to achieving a lightweight upper body for WR-4. In fact, the whole weight of WR-4 (0.85 kg) is lighter than that of WR-3 (1 kg). Furthermore, the lightweight upper body of WR-4 greatly contributes to quicker and more stable rearing action.

3.3. Control architecture

WR-4 is controlled from a PC via wireless communication with the microcontroller STM32F103ZE6T manufactured by STMicroelectronics, Tokyo, Japan. The motor driver circuit board described in Shi *et al.*[20] is able to control six DC motors and two servomotors. The servomotor or USM is driven by a pulse width modulated (PWM) signal generated by a microcontroller, similar to that for DC motor control. Thus, we used the same driver circuit board of WR-3 to control two DC motors, four servomotors, and six USMs (as each shoulder is driven by two USMs, the total number of USMs need to be controlled by the microcontroller is actually four for WR-4). The actions performed by WR-4 mainly include chasing, rearing, rotating, body grooming, and mounting. 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 for each joint angle. Moreover, the current angle of each joint can be obtained based on position feedback by reading a rotary encoder. Thus, on receiving the instructions from the master PC, the microcontroller can immediately update the target angle of each joint by integrating the preloaded time-line motion parameters and current joint angles.

4. Experiments and Discussion

As described previously, WR-4 is developed to interact with real rats. WR-4 should be able to primarily mimic rat behavior, so its motion performance needs to be evaluated. Subsequently, the effectiveness of a novel interaction integrating robot technology (robot–rat interaction) needs to be confirmed by comparison with conventional interaction (rat–rat interaction). Therefore, two types of experiments detailed below were carried out.

4.1. Performance evaluation

To verify the proposed specifications, the motion performance evaluation of WR-4 was conducted. We measured manually the range of waist bending angle θ_{wb} and rearing angle θ_{wr}. As a result, the range of θ_{wb} was between -130° and $+130^\circ$, proving Eq. (2). The maximum angle that WR-4 could rear (θ_{wrm}) was 80°. These two maximum angles met the specifications for mimicking the rearing and rotating actions of rats as shown in Fig. 2. The maximum locomotion speed of WR-4 was 1 m/s, fully meeting the speed requirement for chasing running rats (the mean speed of six running rats is calculated as 0.9 ± 0.11 m/s when chased by a robot in an open field).

For rearing and rotating actions, although the movement range of WR-4 was $0 < \theta_{\mathrm{wr}} < 80^\circ$ and $-130^\circ < \theta_{\mathrm{wb}} < 130^\circ$ respectively, in general rats rear to 60°, and rotate to $\pm 100^\circ$. To effectively and completely obtain the rat behavior data, the maximum angles for rearing and rotating actions were set to 60° and 100° in the following motion performance evaluation. For the rearing action (in the x–z plane), the least time consumed for WR-4 to rear to 10°, 20°, 30°, 40°, 50°, and 60°, from the initial position of 0°, was recorded. In the case of performing rotating action (in the x–y plane), we recorded the least time consumed to rotate through angles of $\pm 20^\circ$, $\pm 40^\circ$, $\pm 60^\circ$, $\pm 80^\circ$, and $\pm 100^\circ$. To guarantee accuracy, we initially recorded videos of all the tests. The least time consumed was then obtained by replaying these videos frame by frame. Every test for WR-4 was repeated thrice, and the results averaged. As a comparison, we also observed the videotaped behavior data at 10-minute intervals for five nine-week rats. For each video clip, we extracted the video segments related to rearing and rotating actions, and the time consumed for the rearing and rotating actions of rats to preset angles (all the values were the same for WR-4) was recorded after replaying the video segments frame by frame. On the basis of action definition, an action is qualified as rearing/rotating when a rat could move at least 60° /100° in no more than 0.8 s/1s. The least time consumed as each rat reared and

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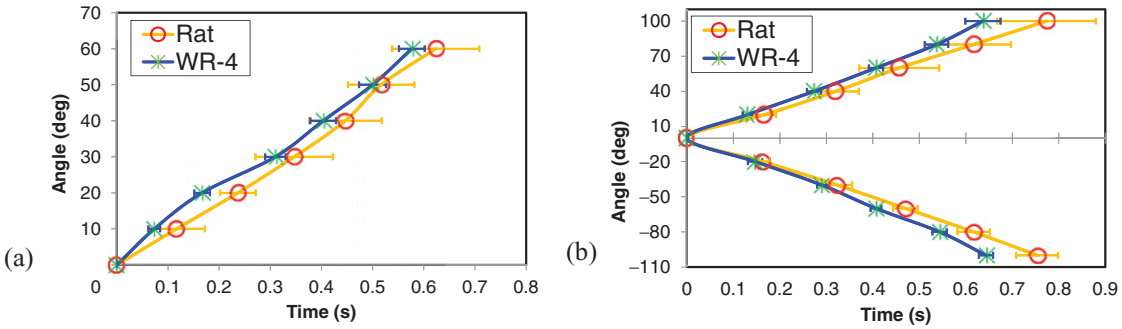


Fig. 8. (Colour online) The motion performance of WR-4 and rats performing rearing and rotating actions. Here the least time to achieve a predetermined angle was recorded. WR-4 could perform both rearing and rotating actions quicker than mature rats when achieving the maximum angle.

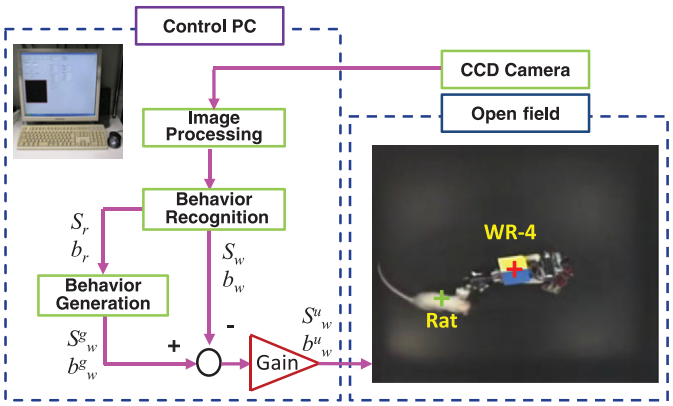


Fig. 9. (Colour online) Experiments are conducted between WR-4 and rats in the open field. WR-4 demonstrated behavior adapted to rat behavior and experimental objectives.

rotated to preset angles could be obtained from the recorded time. The final results were calculated by averaging these least time consumed.

As shown in Fig. 8, when reaching the predetermined maximum angles (rearing: 60°, rotating: ±100°), WR-4 could perform both rearing and rotating actions quicker than mature rats. The excellent motion performance reveals that WR-4 achieved good imitation of rearing and rotating actions of rats in terms of speed and movable range. Thus, the WR-4 robot showed promise for acting like a real rat in robot–rat interactions.

4.2. Interaction between WR-4 and rats

Experiments conducted between rats identified extrinsic influences such as the partner's playfulness in play fighting.[24] The results revealed that play appeared to be contagious, as a highly playful animal stimulated its partner to also play more frequently. In this research we used a rat-like robot that plays the role of a partner in robot–rat interaction. The robot can play socially to entice rats to play excitedly. As stated in Shi *et al.*[20] the robot is able to stimulate the activity of rats when mirroring rearing action. During the interaction, the rats showed considerable interest in the robot, which mirrored their actions, so this type of interaction tended to make rats excited. We called this interaction a *friendly interaction*. By comparison, the *neutral interaction* is defined as the way in which the robot performs without any concern for the actions of the rat. The experiments we conducted involved these two types of interaction.

4.2.1. Experimental setup. The experimental apparatus is shown in Fig. 9. The experimental arena, called an open field, is a flat square, 700 × 700 mm, surrounded by a wooden wall, 600-mm high. The rats and the robot were placed in the open field[12] to conduct the interaction experiments. Based on a CCD camera (solution: 640 × 320 pixels) fixed above the open field, the position and behavior of rats

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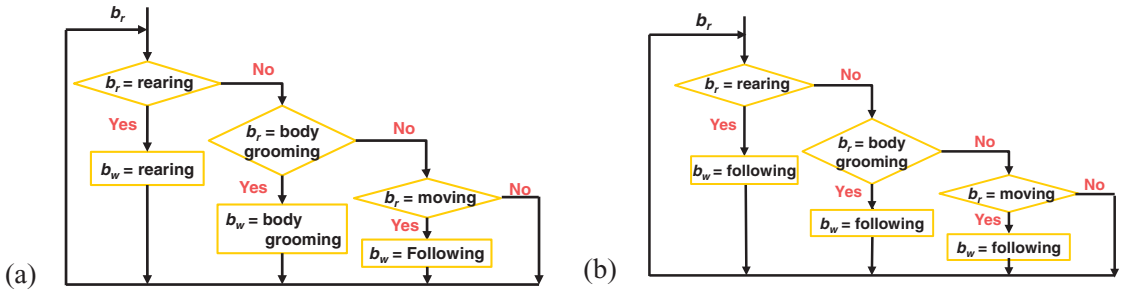


Fig. 10. (Colour online) Behavior generated by WR-4 corresponding to the frequently performed rat behavior. (a) Behavior generated for friendly interaction; (b) behavior generated for neutral interaction.

(S_r, b_r) and WR-4 (S_w, b_w) can be analyzed by a recognition system proposed in refs. [25] and [26]. Receiving commands from the control PC, WR-4 will autonomously generate the behavior pattern (S_w^g, b_w^g) corresponding to rat behavior and experimental objectives. WR-4 then update actions (S_w^u, b_w^u) according to the integration of S_w, b_w and S_w^g, b_w^g. Consequently, the experiments were performed in the enclosure and operant chamber autonomously without human intervention.

4.2.2. Methods and materials. Behavior generation for friendly and neutral interaction is shown in Fig. 10. Here the friendly interaction was supposed to be conducted as follows: the robot follows the rat, and mirrors its actions of rearing and body grooming. As in our former research, this type of behavior appeared to elicit excitement in rats. The behavior the robot performs in this case is defined as *friendly behavior* (Fig. 10(a)). For neutral interaction, the robot continuously follows the rat. In this case, we assume that the robot puts out *neutral behavior* (Fig. 10(b)) for interacting with rats. We hypothesize that friendly behavior on the part of the robot will increase the frequencies of the actions of rearing, grooming, and approaching the robot as well as decrease robot–rat distance during the interaction and evaluation phases when compared with neutral behavior. The activity can be specified by the amount of movement a_m, the rearing frequency (the number of rearing actions in one minute) f_r, and the body grooming frequency (the number of body grooming actions in one minute) f_g.[9] Furthermore, we considered that the rat's interest in the robot to be a significantly important index of relationship with the robot. If the rats showed more interest in the robot, they would move toward and approach the robot more frequently (refers to the frequency of rats approaching the robot f_{ar}, and the robot–rat distance, $d_{\mathrm{rb-r}}$).[27]

Twelve experimental rats from the same litter were used. They were males, weighed 201.3 ± 4.09 g, and were reared in the same housing conditions. All the rat subjects therefore had similar activity amongst one another before the experiments. We divided these rats into two groups, with six seven-week old 344/Jcl rats in each group (A_i, B_i, where $i = 1, \ldots, 6$) [http://www.clea-japan.com/animalpege/a 1/e 07.html]. The Group A rats were exposed to robot exhibiting friendly behavior, while the Group B rats were exposed to the robot exhibiting neutral behavior. The specific experimental procedures for each group can be seen in Fig. 11. In the first T_i (10 minutes), that is the interaction phase, WR-4 exhibited friendly behavior toward the rats in Group A, and neutral behavior toward the rats in Group B. In the remaining T_e (5 minutes), that is the evaluation phase, the robot stayed immobile at the center of the open field. The same experiment was conducted continuously for 6 days. We scored the amount of movement (a_m^i and a_m^e), the rearing frequency (f_r^i and f_r^e) and the body grooming frequency (f_g^i and f_g^e) in the rats during the interaction and evaluation phases, as well as how frequently the rats approached the robot and the robot–rat distance $d_{\mathrm{rb-r}}^e$ during the evaluation phase. The frequency of the rats approaching the robot and the robot–rat distance may vary with the locomotion of the robot during the interaction phase, especially for the experiments with Group B, in which the rats were continuously followed by the robot. Therefore these two parameters were scored only in the evaluation phase. f_r^i, f_r^e, f_g^i, and f_g^e were measured based on the system proposed in ref. [26] whereas a_m^i, a_m^e, f_{ar}^e, and $d_{\mathrm{rb-r}}^e$ were obtained based on the system described in ref. [25].

4.2.3. Results. Averaging the measured parameters, we obtained mean frequency for the actions of rearing, body grooming and approaching the robot, the mean robot–rat distance, and the mean amount of movement in each rat. Similarly, the total mean values for each parameter with respect to each

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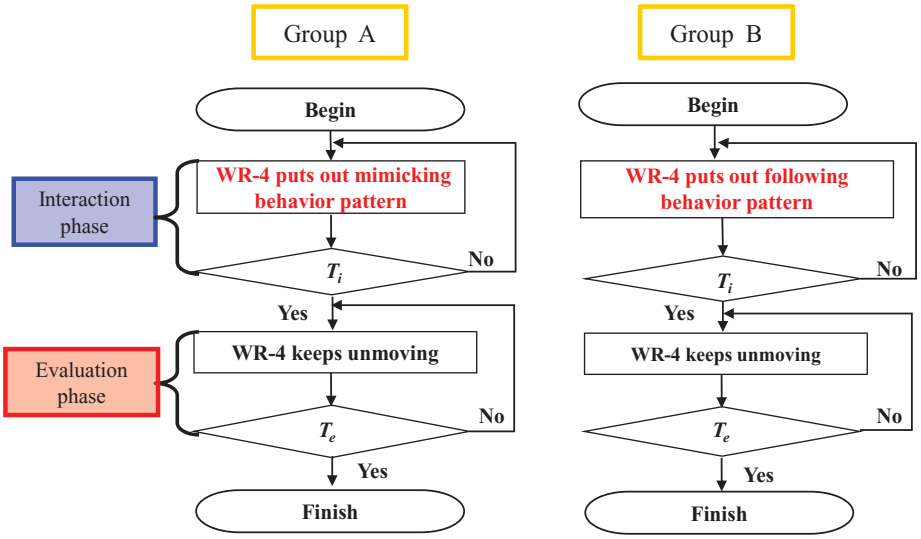


Fig. 11. (Colour online) Interaction experimental procedures of WR-4 with Group A and B rats. T_i, threshold time of the robot interacting with rats, is 10 minutes; T_e, threshold time of the robot remaining static, is 5 minutes.

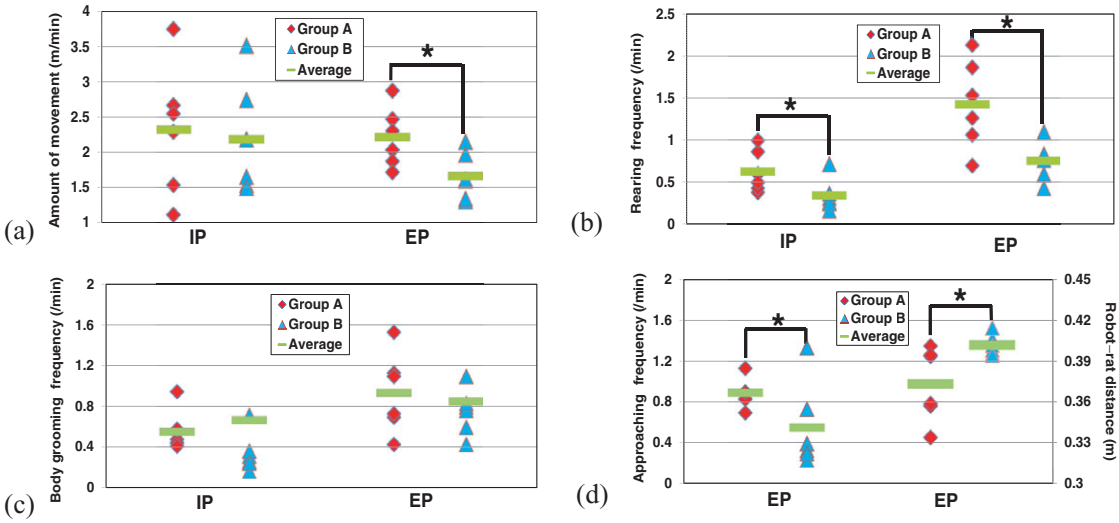


Fig. 12. (Colour online) Mean frequency for the actions of rearing, body grooming and approaching the robot, the mean robot–rat distance, and the mean amount of movement of each rat subject in Groups A and B. Note that red rhombus denotes value for rat in Group A, blue triangle denotes value for rat in Group B, green rectangle denotes mean value for all rats in a group, IP means interaction phase, and EP means evaluation phase (Student's t-test n = 6; $^{*}p < 0.05$).

group were calculated. As shown in Fig. 12, the a_m^i, f_g^i, and f_g^e values for rats in both groups were quite similar although a_m^e, f_r^i, f_r^e, and f_{ar}^e values for rats in Group A were significantly more than those for rats in Group B, while the $d_{\mathrm{rb-r}}^e$ values for rats in Group A were significantly less than those for rats in Group B. The higher values for a_m^e, f_r^i, and f_r^e suggest that most of the rats in Group A were more active than those in Group B. These results concur with the findings described in Varlinskaya *et al.*[27] Furthermore, the higher values of f_{ar}^e and the lower values of $d_{\mathrm{rb-r}}^e$ reveal that rats in Group A show greater preference for interacting with the robot.

4.2.4. Evaluation and discussion. In order to confirm the effectiveness of the robot–rat interaction, similar experiments were conducted between real rats (rat–rat interaction). The rat–rat interaction experiments were also conducted in the experimental apparatus as shown in Fig. 9. Twelve male rats (seven-week old F344/Jcl) divided into two groups: Group C and Group D, with six rats in each group.

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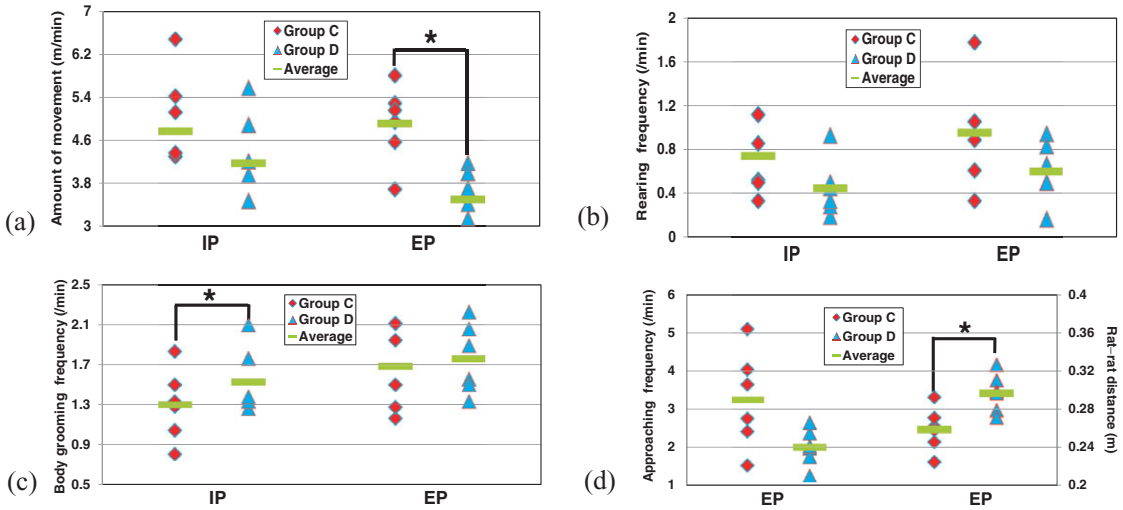


Fig. 13. (Colour online) Mean frequency for the actions of rearing, body grooming and approaching the stuffed rat, the mean rat–rat distance, and the mean amount of movement of each rat subject in Groups C and D. Note that red rhombus denotes value for each rat in Group C, blue triangle denotes value for rat in Group D, green rectangle denotes mean value for all rats in a group, IP means interaction phase, and EP means evaluation phase (Student's t-test n = 6; *p < 0.05).

Similar to the robot–rat interaction, all the rat subjects were from the same litter, weighed 198.2 ± 4.41 g, and were reared in the same living conditions to guarantee similar activity between them. However, it is quite likely that the relationship between real rats varies with partners, so preliminary interaction tests were conducted to select a suitable partner for each rat. All the partner rats were also seven-week old, and weighed about 200.8 ± 5.88 g. Here $C_i = D_i$ ($i = 1...6$) is supposed to be a rat subject of Group C/D. In the preliminary experiment a $C_i = D_i$ rat subject was placed in the open field to interact with one of the partner rats for 10 minutes. During the interaction, a partner rat that interacted in a friendly way with C_i (actively playing with each other, and rarely attacking or biting it) was considered to be its friendly partner F_i. Conversely, a partner that interacted neutrally (less concerned with each other) with D_i was considered to be its neutral partner N_i. We selected a friendly partner F_i for C_i, and a neutral partner N_i for D_i. For better identification, all the partner rats were colored blue during the experiments. Similar to the experiment procedure illustrated in Fig. 11, the rats interacted with live rat partners during the interaction phase. However, in the evaluation phase the partner was replaced by a stuffed rat made from a mature real rat as shown in Fig. 1. The same experiment was also continuously conducted for six days. We measured a_m^i, a_m^e, f_r^i, f_r^e, f_g^i, f_g^e, f_{ar}^e, and $d_{\mathrm{r-r}}^e$ (rat–rat distance) during each experiment. The results averaged from these measured values are shown in Fig. 13.

Similar to robot–rat interaction, the significant differences were confirmed in a_m^e and $d_{\mathrm{r-r}}^e$ values. Furthermore, the f_r^i, f_r^e, and f_{ar}^e values for rats in Group C were mostly more than those for rats in Group D, which was almost similar to robot–rat interaction. The f_g^i values for rats in Group C were significantly less than those in Group D, which was also similar to robot–rat interactions. Conversely the f_g^e values for rats in Group C were less than those in Group D. Thus WR-4 could not simulate the body grooming action as well as the rearing action of rats, mainly because it could not imitate the body grooming action realistically because of its limited mechanism. However, the majority of Group C rats were more active and showed greater interest in their partners than those in Group D, which was significantly close to the results of robot–rat interaction. The evaluation therefore proves the efficacy of the robot–rat interaction system. In addition, we calculated STDEVP (an Excel Statistical Function) of each parameter as shown in Table I. The STDEVP for most parameters of Groups A/B were smaller than for Groups C/D. The experimental procedures for Groups A and C and Groups B and D were similar. It is because the relationship between two rats would change slightly during the interaction even if we chose friendly/neutral partner for rats in Groups C and D. Thus, the interaction between living rats is difficult to control and has poor reproducibility as we argued in Section 1. On

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Table I. STDEVP of each parameter.

	Parameter							
Group	a_m^i	a_m^e	f_r^i	f_r^e	f_g^i	f_g^e	f_{ar}^e	d^e
A	0.841	0.387	0.326	0.459	0.184	0.359	0.128	0.025
C	1.099	0.657	0.308	0.448	0.324	0.387	1.157	0.021
B	0.734	0.307	0.198	0.206	0.236	0.248	0.383	0.007
D	0.862	0.535	0.238	0.253	0.301	0.319	0.441	0.018

the other hand, fewer variances of parameters occurred in robot–rat interactions, suggesting that the robot seemed to control rat behavior more effectively. This robot–rat interaction system therefore has the promise of enabling adjustment of rat behavior in the same way as in real rats, and has better controllability and reproducibility.

As stated in Section 1, these parameter scores are also the indices signifying sociality and anxiety of rats. The robot–rat interaction enables the evaluation of sociality and anxiety of RMMDs, which are related to the degree of mental disorder. Thus, this novel interaction system can contribute to clarifying the mechanism of mental disorder and screening psychotropic drugs.[28] Furthermore, in contrast to agonistic interaction, friendly interaction may to some degree decrease the anxiety level of rats. Therefore, the friendly interaction between the robot and rats also has promise for alleviating or treating mental disorder. In the future, this novel robot–rat interaction experiment can replace conventional social interaction test to evaluate RMMDs, which have a higher level of anxiety than normal rats, showing lower activity (less amount of movement, fewer frequencies of actions, etc.). Consequently, an evaluation experiment can be designed as follows: We expose several RMMDs developed based on the method described in Ishii *et al.* (2010)[7] to a friendly robot. As a comparison, the same number of normal rats will be exposed to a neutral robot. As a result, if showing similar activity to normal rats these RMMDs had been induced mental illness, then this verifies the effectiveness of the development method of RMMDs as well.

However, more realistic results can be obtained by taking into consideration the effects of smell and sound as well as the fur covering. Furthermore, to improve the generalizability of results, different experimental conditions need to be considered, such as conducting experiments on different ages of rat subjects, extending the duration of each experiment, or placing multiple rats together with the robot in the experimental field. In addition, behavior analysis, anatomical analysis, and bioanalysis should be conducted to provide more comprehensive results. Nevertheless, the current work opens novel insights and possible new forms for animal behavior research in the future.

5. Conclusions and Future Work

5.1. Conclusions

This paper explained the design and development of WR-4 robot intended for interacting with live rats. Based on the behavioral model of mature rats, the robot body framework and DOF configuration were determined. The waist equipped with a multi-bendable six-bar linkage mechanism allows the robot to rotate $\pm 130^\circ$ horizontally, meeting the required movement range for mimicking rat behavior. The integration of the multi-bendable waist and the four-bar linkage mechanism in the neck achieves a bending posture similar to live rats, allowing the imitation of rearing and body grooming actions. Furthermore, the USM used to drive forelegs reduces the upper body by about 200 g, resulting in lower inertia and quicker performance of the rearing action. Evaluation tests on the performance of rearing and rotating actions were conducted. The test results show that WR-4 can perform both rearing and rotating actions quicker than live mature rats when reaching the predetermined maximum angles, endowing it with almost the same motion performance as that of live mature rats.

Following strict psychological rules, interaction between WR-4 and the two groups of rats was conducted in an open-field environment. Experimental results reveal that the activity of rats exposed to a friendly robot can be improved significantly over rats exposed to a neutral robot. The increased approaching frequency and the decreased robot–rat distance show that rats prefer to stay with the

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robot that has exhibited motion patterns mimicking the rat behavioral elements (rearing and body grooming). Furthermore, compared with rat–rat interaction, there are fewer individual differences in the experimental results of robot–rat interaction, illustrating better controllability and reproducibility. Consequently, the proposed novel methodology achieves the analysis and adjustment of rat behavior with high success rates and reproducibility, to a level significantly meaningful for research on RMMDs.

5.2. Future work

We would like the robot to do newer types and variations of social behaviors by developing new motion patterns and combining the current motion patterns. Through the analysis of experimental results, we expect to determine more behavioral patterns on how to specifically influence rat behavior (for instance, changing activity and inducing certain social behavior). Consequently, we could make the robot mimic such types of social behavior to create stronger influences on rats and achieve effective results. Finally, as a long-term objective, we would like to develop a robot that can automatically interact with rats and convey a completely natural impersonation to live rats. In addition, we intend to propose a mathematical model to specify relationship between rat behavior and robot behavior. Based on the mathematical model, the variation in rat behavior could be quantitatively controlled by the robot. Conversely, robot behavior can be generated that will result in the required rat behavior.

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