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Control of Posture and Trajectory for a Rat-like Robot Interacting with Multiple Real Rats

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***Abstract*— In the past we achieved to use a rat-like robot and a single rat to develop Animal Models of Mental Disorder (AMMDs) through stress exposure. However, to simulate the real social environment, we use a rat-like robot composed of multiple links to chase a specific rat (target) in a group of rats (outside observers). In this paper, we aim to develop a real-time control system for a multi-link robot surrounded by multiple rats. A virtual impedance model was adopted to generate posture and trajectory for a multi-link robot named WR-5. With the analysis of virtual forces/moments acting on WR-5 based on the model, corresponding dynamic equations can be obtained to control the motion of WR-5. Simulation results show that the head of WR-5 can accurately direct a target object in the following test. After conducting experiments with three rat subjects (a target rat, two outside observers), the output results suggest that the head and body gesture of WR-5 achieves to follow the target in real-time. Meanwhile, the control system allows real-time avoidance of the moving outside observers during interaction.**

I. INTRODUCTION

Recently, bio-inspired robots have been greatly contributing to studies on animal behavior in ethology, animal psychology, and behavioral biology [1]. Actually, biorobotics provides tools for biologists studying animal behavior and test beds for the study and evaluation of biological algorithms for potential engineering applications. Specifically, use of these bio-inspired robots offers novel methodologies to study response of an animal to the stimulus from the same species or other species. For instance, these bio-inspired robots are used to understand decision making of an individual or a group of animals such as insects [2], [3], [4], [5], birds [6], fishes [7], and rodents [8].

On the other hands, experiments on animal behavior have been playing a very important role in psychic medicine [9], [10], [11], [12], [13]. All psychotropic drugs have been evaluated in experiments with Animal Models of Mental Disorder (AMMDs) before used in clinical practice [9]. These experiments are called drug screening test. AMMDs are living animals that represent phenotypes of human patients with mental disorders. In general, they are produced based on genetic manipulation [14], nerve surgery [15], or stressful environment [16]. In a drug screening test, a newly developed drug is administered into an animal model, and its effect is then evaluated through behavior observation. Rodents such as rats and mice are commonly selected as experimental subjects in these tests due to their genetic consistency and similarity with human beings in their reaction to drugs. Recently, several new psychotropic drugs are developed through these tests [12], [13]. However, some researchers have mentioned the limitations of conventional AMMDs because of low predictive validity (performance in the test predicts performance in the condition being modeled), face validity (phenomenological similarity) and construct validity (theoretical rationale) [17]. We proposed to use robot technology to break through these limitations in the drug screening test [18], [19]. In this method, animal models of depression can be developed by exposing continuous attack from a robot in immature period and interactive attack in mature period. This method is confirmed to be able to develop AMMDs with construct validity and face validity.

In our previous research, the stress exposure tests are performed with one robot and one rat. However, rats are social animals, gaining much enjoyment and stimulation from each other's company [20]. They live in large family groups in the wild. So rats may interact with the robot in a more natural way if kept with more companions. As proposed in this paper, we put a robot together with multiple rats. In this novel stress exposure system, the robot continuously attacks a specific rat (we call it as a target rat). The other rats are considered as outside observers, which should be avoided by the robot during the experiment. Therefore the motion planning of the robot can be regarded as chasing the target rat and simultaneously avoiding outside observers. There are many examples in the field of self-collision avoidance control [21], [22], [23]. Especially some algorithms were able to generate optimal trajectory for a small mobile robot, for instance, potential field method (PFM) [22], voronoi diagram method (VDM) [23]. However, the computational cost of PFM is very high in case of avoiding multiple dynamic obstacles, resulting in severe delay. VDM can be implemented very fast though, it is not suitable to control the posture of a rat-like robot consisting of multiple links.

To solve these above-mentioned shortcomings, we adopt

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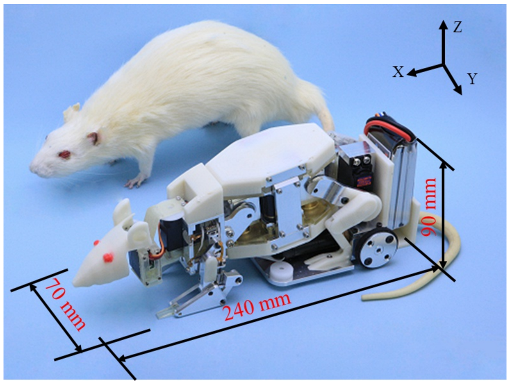

Fig. 1. The rat-like mobile robot named WR-5, and a stuffed rat made from a real, mature rat.

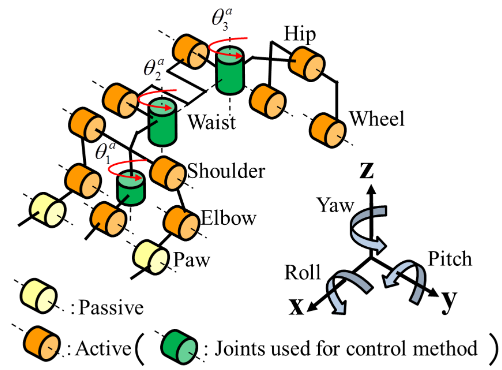

Fig. 2. DOF arrangement of WR-5 is determined on the behavioral model, anatomy pictures and motion analysis of rats. θ_1^a, θ_2^a, θ_3^a are rotational angles of the joints used for the virtual impedance model described in Section.II-B. (See also Fig.3)

a virtual impedance model ([24], [25]) to build a real-time control system for a rat-like robot to interact with multiple rats. With the analysis of virtual forces/moments acting on WR-5 based on the model, corresponding dynamic equations can be obtained to control the motion of WR-5, acting with optimal posture and trajectory. Simulation results showed that the head of WR-5 can accurately towards a target object in the following test. Furthermore, we put WR-5 together with three rat subjects (a target rat, two outside observers) to validate this model. Experimental results suggest that WR-5 achieves to adjust its posture to chase the target rat in real-time. Meanwhile, the implementation of this control system allows real-time avoidance of the moving outside observers during interaction.

This paper is organized as follows. In Section II, we present a description of the robotic platform and virtual impedance model based control method. In Section III, we experimentally and analytically study the control system, and perform experiments and analysis of robot-rat interaction. Finally, conclusions and future work are summarized in Section IV.

II. MATERIALS AND METHODS

A. Robot Agent

Building on the experiences gained from previous robot prototypes, we developed a novel rat-like robot named WR-5 as shown in Fig.1 (size: $70 \times 240 \times 90$ mm, weight: 0.8 kg) [26]. The body framework and DOF configuration of WR-5 was determined with analysis of X-ray structure of rat behavior. The skeleton structure of WR-5 is represented by the DOF arrangement as depicted in Fig.2: 13 active DOFs and 2 passive DOFs in the paws. Performance evaluation confirmed that WR-5 could perform both rearing and rotating actions faster than live mature rats, which endowed WR-5 with almost the same motion performance as rats. The interaction experiments between WR-5 and mature rats have been conducted strictly following psychological rules. Experimental results showed that rats were more active and had fewer frequencies of body grooming and rearing actions when WR-5 performed mounting action periodically. The rat-like robot was therefore able to make the anxiety level of rats high by means of performing mounting action.

Besides, to recognize and analyze rat behavior automatically, we furnished the robot with a recognition system [27] based on image processing and classification techniques. In the recognition system, basic image processing algorithms as Labeling and Contour Finding were employed to extract feature parameters such as body area, circularity, rotational angle and speed to discriminate rat behavior. These feature parameters served as the input vector of Support Vector Machine (SVM) for classification. Experimental results revealed that the rearing, body grooming and rotating actions could be classified with more than 90% accuracy by this recognition system, which was sufficient for the analysis of rat behavior.

B. Virtual Impedance Model

As shown in Fig.2, there are 3 DOFs in the yaw direction. WR-5 can therefore be divided into four links (l_0^1: head-neck, l_1^2 and l_2^3: waist, l_3^4: hip). A virtual impedance model is adopted to generate posture and trajectory for WR-5. The model defines virtual masses, springs, dampers between the links l_i^{i+1} of WR-5 (Fig.3). The model determines the motion of each link by means of virtual force. It consists of three parts: the force generated between the robot and the target rat, the force generated between two links, the force generated between a link and a outside observer. To better understand this model, first we explain a simple case: the robot put together with one outside observer and one target rat. The outside observer generates repulsive forces F_i^r to all the joints, while the target rat only generates attractive force F^a to the head. As shown in the following equations, the virtual forces are determined by the distance between rat subjects and the robot.

$$F^a = C^a \cdot \sqrt{(x_t - x_0)^2 + (y_t - y_0)^2} \tag{1}$$

$$F_i^r = C^r \cdot \frac{1}{(x_{ob} - x_i)^2 + (y_{ob} - y_i)^2} \tag{2}$$

Where (x_t, y_t), (x_{ob}, y_{ob}), $(x_i, y_i)(i = 0 \sim 3)$ are the position coordinates of the target rat, the outside observer, and the joints of the robot. C^a, C^r are the gain coefficients.

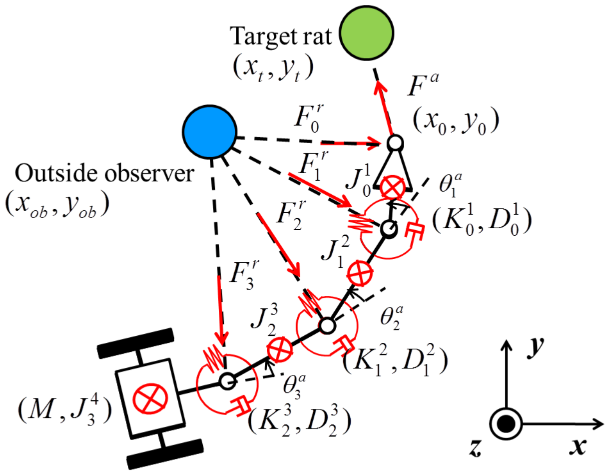

Fig. 3. A simple virtual mass-spring-damper model of WR-5. Green ball denotes the target rat, blue ball denotes the outside observer; $i = 0 \sim 3$: joint number; J_i^{i+1}: virtual moment of inertia of link l_i^{i+1}; F_i^r: virtual repulsive force acting on joint i generated by the outside observer; F^a: virtual attractive force generated by the target rat; K_i^{i+1}, D_i^{i+1}: virtual spring/damper coefficients; M: virtual mass of hip part; $(x_{ob}, y_{ob}), (x_t, y_t), (x_i, y_i)$: position coordinates of the outside observer, the target rat, each segment of the robot.

Take the hip part as reference object, there is only rotational motion of waist-neck-head part. Given virtual moment of inertial J_i^{i+1}, rotational angle θ_i^a, virtual spring/damper coefficients K_i^{i+1}, D_i^{i+1}, the torque N_i of each joint $i = 1 \sim 3$ can be derived from the following equation based on Newton's second law.

$$\mathbf{N} + \mathbf{K} \cdot \mathbf{q} + \mathbf{D} \cdot \dot{\mathbf{q}} + \mathbf{J} \cdot \ddot{\mathbf{q}} = \mathbf{0} \tag{3}$$

Where
$q = (\theta_1^a, \theta_2^a, \theta_3^a)^T$,
$N = (N_1, N_2, N_3)^T$,
$K = diag(K_0^1, K_1^2, K_2^3)$,
$D = diag(D_0^1, D_1^2, D_2^3)$,
$J = diag(J_0^1, J_1^2, J_2^3)$.

Subsequently, we will show the force analysis of each joint (Fig.4). Based on the model, a joint i will receive a repulsive force F_i^r generated by the outside observer, two forces F_i^a and $-F_{i+1}^a$ generated by its adjacent joints $i-1$ and $i+1$. Besides, a torque N_i is generated based on the virtual spring-damper model on joint i and the synthesis of forces acting on its former joint $i-1$. The analysis of force is shown in Fig.4. In particular, regarding the first joint (head point) j_0, $F_0^a = F_a$, F_0^r is calculated based on (2), $N_0 = 0$. For the other joints, F_i^a and N_i can be calculated by the following equation.

$$\begin{bmatrix} F_{i+1}^a \\ N_{i+1} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & l_i \end{bmatrix} \cdot \begin{bmatrix} \cos\theta_i^a & \cos\theta_i^r \\ \sin\theta_i^a & -\sin\theta_i^r \end{bmatrix} \cdot \begin{bmatrix} F_i^a \\ F_i^r \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ K_i^{i+1} & D_i^{i+1} \end{bmatrix} \cdot \begin{bmatrix} \theta_{i+1}^a \\ \dot{\theta}_{i+1}^a \end{bmatrix} \tag{4}$$

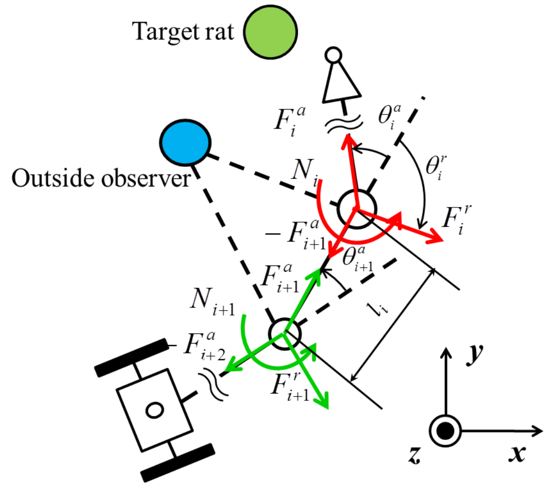

Fig. 4. Force analysis of a joint for the waist-neck-head part of WR-5. l_i denotes the length of link, θ_i^r denotes the angle between repulsive force F_i^r and link l_i^{i+1}.

Where, l_i denotes the length of link l_i^{i+1}, θ_i^r denotes the angle between repulsive force F_i^r and link l_i^{i+1}.

Finally, regarding the hip part, a virtual spring-damper model (K_w^a, D_w^a) between the robot head and the target is added (Fig.5). Similar to (4), F_4^a is determined by calculating the synthesis of forces (F_3^a and F_3^r) acting on joint 3. Regarding N_4, it consists of the torque generated by the synthesis of F_3^a and F_3^r, the torque generated by (K_w^a, D_w^a). However, when the robot head goes very near to the target rat, to avoid hitting it, a virtual inertia damper D_w^x is introduced to stop the robot. Here we assume that v_1 is the linear velocity of left wheel, v_2 is the linear velocity of right wheel. The speed of the centroid of hip part can be calculated as $\bar{V} = (v_1 + v_2)/2$. In addition, θ_w^x denotes the angle with respect to x-axis. Thus the force equation of hip part can be derived as following.

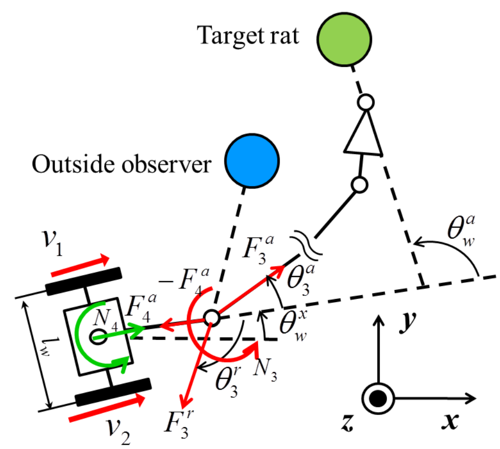

Fig. 5. Force analysis of the hip part of WR-5.

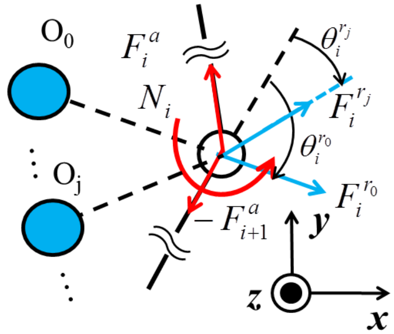

Fig. 6. Repulsive force analysis in case of multiple outside observers.

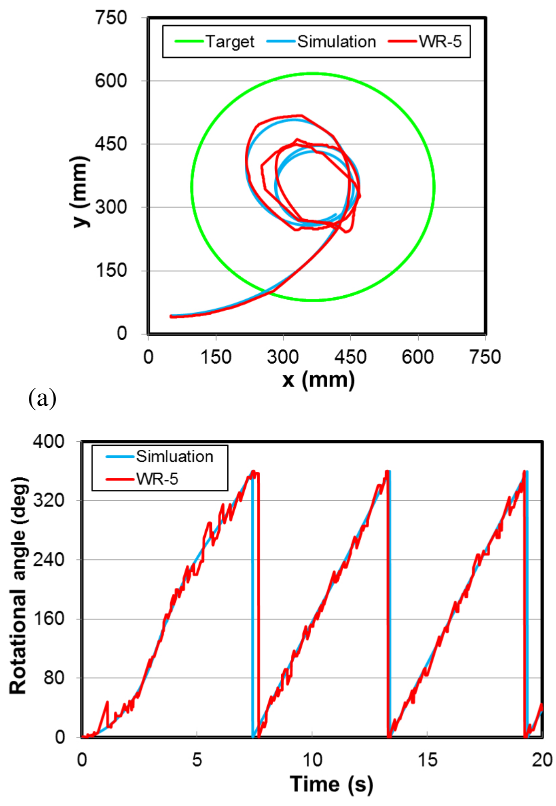

Fig. 7. Following test results of a simulated robot and WR-5. (a) Trajectories of the centroids of a simulated robot and WR-5; (b) The angle with respect to x-axis of a simulated robot and WR-5.

$$\begin{bmatrix} F_4^a \\ N_4 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & l_3 \end{bmatrix} \cdot \begin{bmatrix} \cos\theta_3^a & \cos\theta_3^r \\ \sin\theta_3^a & -\sin\theta_3^r \end{bmatrix} \cdot \begin{bmatrix} F_3^a \\ F_3^r \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ K_w^a & D_w^a \end{bmatrix} \cdot \begin{bmatrix} \theta_w^a \\ \dot{\theta}_w^a \end{bmatrix} + \begin{bmatrix} D_w^x & 0 \\ 0 & D_w^x \end{bmatrix} \cdot \begin{bmatrix} \bar{V} \\ \dot{\theta}_w^x \end{bmatrix} \tag{5}$$

Given the mass M, the moment of inertia J_3^4, the width l_w between two wheels, the linear accelerators of the left and right wheels can be calculated based on the following equation.

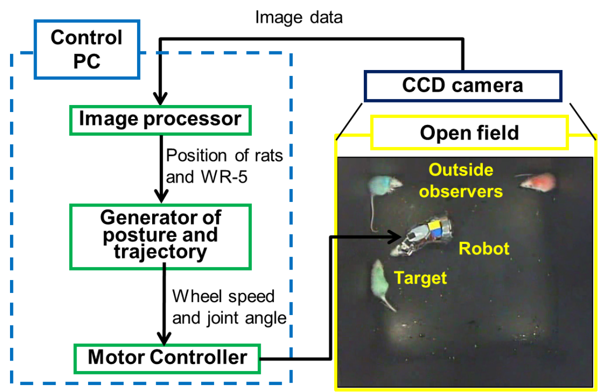

Fig. 8. Experimental setup for WR-5 and three rats in a test. Three rats are colored with red, cyan and green respectively. WR-5 is continuously chasing the green rat in the experiment.

$$\begin{bmatrix} \dot{v}_1 \\ \dot{v}_2 \end{bmatrix} = \begin{bmatrix} 1/M & l_w/(2 \cdot J_3^4) \\ 1/M & -l_2/(2 \cdot J_3^4) \end{bmatrix} \cdot \begin{bmatrix} F_4^a \\ N_4 \end{bmatrix} \tag{6}$$

However, the equations listed above are satisfied only when there is one repulsive force. In case of multiple outside observers, we assume the number of outside observers is n. Each outside observer $O_j (j = 0 \sim n)$ generates a repulsive force $F_i^{r_j}$ to the link l_i^{i+1}. Given the angle $\theta_i^{r_j}$ between repulsive force $F_i^{r_j}$ and link l_i^{i+1}, we can update F_{i+1}^a, N_{i+1} using the following equations.

$$F_{i+1}^a = F_{i+1}^a + \sum_{j=1}^{n-1} F_i^{r_j} \cos\theta_i^{r_j} \tag{7}$$

$$N_{i+1} = N_{i+1} - l_i \cdot \sum_{j=1}^{n-1} F_i^{r_j} \sin\theta_i^{r_j} \tag{8}$$

As proposed in [25], we determined the following design parameters by using trial and error method: C^a, C^r, J_i^{i+1}, K_i^{i+1}, D_i^{i+1}, M, K_w^a, D_w^a, D_w^x. Furthermore, the position and angle parameters ($(x_{ob}, y_{ob}), (x_t, y_t), (x_i, y_i)$, θ_w^x, θ_i^r) can be calculated based on the recognition system [27]. Consequently, integrating equations (1),(2),(3),(4),(5),(6), we can obtain required linear velocity of each wheel (v_1, v_2) and rotational joint angle (θ_i^a).

III. PERFORMANCE EVALUATION AND EXPERIMENTS

A. Performance Evaluation

We developed a simple simulated environment: a four-link robot and a circle target surrounded by a 700×700 mm open field. The target moves in a circle path at a speed of 0.3 m/s, while the robot is simulated to continuously follow it. The posture and trajectory of the simulated robot is generated based on the virtual impedance model. We tracked the position data of the simluated robot and the target (the blue line in Fig.7(a)), and the angle of hip part with x-axis θ_w^x (the blue line in Fig.7(b)). These results show that the simulated robot was able to closely chase the

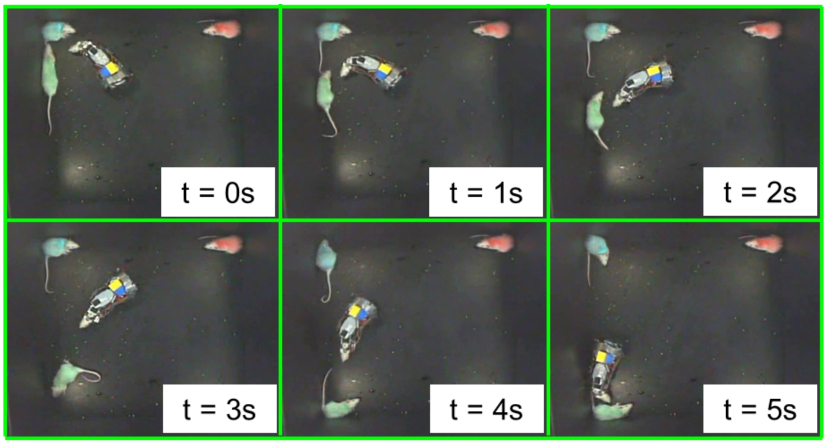

Fig. 9. Screenshot of the robot-rat interaction experiment. The multi-link robot WR-5 is able to adjust its posture to directly towards the direction of the green rat (target). In the meantime, WR-5 can adjust its posture to avoid the cyan and red rats (outside observers).

target. Additionally, we conducted similar experiments by putting WR-5 in a real 700×700 mm open field. WR-5 was controlled to follow a virtual target moving in a circle path, its trajectory and rotational angle θ_w^x were measured as well (the red line in Fig.7). The trajectory of WR-5 is quite similar to the simulated robot, confirming the effectiveness of this control method.

To verify the effectiveness of proposed control method, the WR-5 was used to chase real rats as well. We used three 9-week old F344/Jcl male rats in this experiment. The experimental arena referred to as the open-field which is a flat 700×700 mm, surrounded by a wooden wall with a height of 600 mm (Fig.8). The three rats were colored with red, cyan and green respectively for classification. Based on image processing, positions of the rats and WR-5 could be detected by a CCD camera (resolution:640×320 pixels) installed at the top of the open field. Receiving generated posture and trajectory from a external control PC, WR-5 could autonomously chase a specific rat (the target that is colored with green here).

As shown in Fig.9, for each test WR-5 was continuously chasing the green rat in the open field. Simultaneously, WR-5 was trying to avoid the cyan and red rats. The tests were repeatedly conducted 6 times in total. Based on the positions of the rats and WR-5, we calculated their distances in each one-minute interval (Fig.10). For the mean distance to WR-5, the green rat had the lowest value in every minute, which was ranged from 25.5 cm to 40.9 cm. Whereas that of the red and cyan rats was from 49.1 cm to 70.3 cm, and from 55.3 cm to 66.9 cm, respectively.

In summary, both simulation and actual following tests demonstrate that the virtual impedance model based control system allows the robot to keep on chasing a specific target in real-time. In particular, the posture of the robot head was controlled to aim at the target rat all the time, greatly improving the similarity with the posture of real rats. It therefore gives the possibility that our method can be used to control the posture and trajectory of the rat-like robot to better mimic real rats. The control method also enables the robot to avoid other outside observers in real time. Especially, during the experiment we found that the robot can adjust its posture to avoid dynamic obstacles (moving outside observers). Thus this control system can be used for the control of the posture and trajectory of a rat-like robot consisting of multiple links. Besides, during following test the outside observers felt fear to the robot at the beginning. However, they might show interest to the robot when they were aware of not being attacked. As shown in Fig.11, the gradually reduced distance between the outside observers (red and cyan rats) and WR-5 improves this possibility. Conversely, the target rat seemed to feel helpless during the chasing process. Compared with the AMMDs developed in a environment with one robot and one rat [18], much more stress might be induced in the rat receiving such kind of chasing. The idea that exposing stress to a specific rat in a group of rats promises to be a more effective method to develop AMMDs. Thus it can be further used for application in screening of psychotropic drugs.

IV. CONCLUSIONS AND FUTURE WORKS

To imitate the social environment for rats, we proposed to use multiple rats to interact with a rat-like robot. Based on

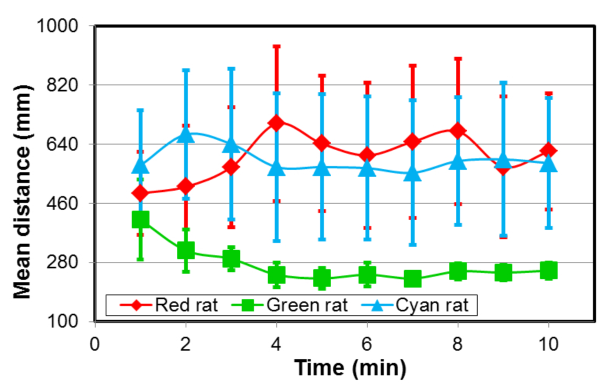

Fig. 10. Mean distance between the robot and rats with respect to time.

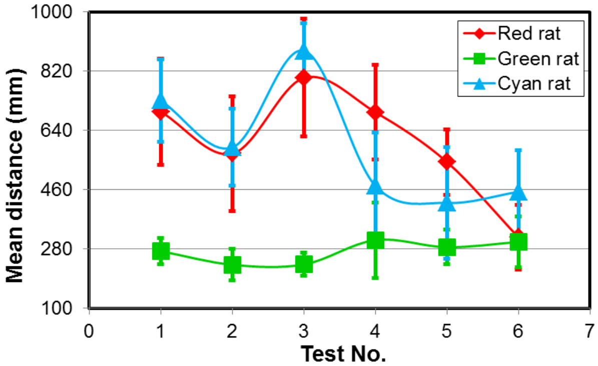

Fig. 11. Mean distance between the robot and rats with respect to each test.

a virtual impedance model, a real-time control system was developed to generate the posture and trajectory for a rat-like robot composed of multiple links. With the analysis of virtual forces/moments acting on WR-5 based on the model, corresponding dynamic equations can be obtained to control the motion of WR-5. Simulation results show that the head of WR-5 can accurately towards a target object during the following test. Furthermore, WR-5 was put together with three real rats (a target rat, two outside observers) to validate this model. Experimental results demonstrate that WR-5 can adjust its head and body gesture to follow the target rat in real time. Meanwhile, the control system allows real-time avoidance of the moving outside observers during interaction.

However, current robot system is still improvable especially in the following aspects. First, the control method should be optimized to allow the robot to act more similarly to a real rat. Furthermore, we need to evaluate the effectiveness of the motion similarity to real rats. When the effectiveness of motion similarity is confirmed, we can then perform the robot-rat interaction in a more natural way. For the future realistic application, we can output agonistic behavior to interact with multiple rats to develop AMMDs.

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