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Development of a Novel Quadruped Mobile Robot for Behavior Analysis of Rats

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Abstract—**In the domain of psychology and medical science, many experiments have been conducted referring to research on animal behaviors, to study the mechanism of mental disorders and to develop psychotropic drugs to treat them. Rodents such as rats are often chosen as experimental subjects in these experiments. However, according to some researchers, the experiments on social interactions using animals are poorly- reproducible. Therefore, we consider that the reproducibility of these experiments can be improved by using a robotic agent that interacts with an animal subject. We have developed a novel quadruped rat-inspired robot, the WR-2 (Waseda Rat No.2), based on the dimension and body structure of a mature rat. It is capable of reproducing the behaviors such as walking, mounting, rearing and grooming of the rat.**

I. INTRODUCTION

In recent years, the number of patients with mental illness has been sharply growing due to social stress [1]. To work against such a serious situation, much attention towards mental disease therapy has been paid. Many experiments on animals have been performed to develop new psychotropic drugs for mental disorders. In these experiments, new drugs are given to disorder model rats. The validity of these drugs has been evaluated through several behavioral tests, such as the social interaction test, the open-field test, the forced swimming test and the fear conditioning test [2] [3].

Regarding the mental disorders of humans, social interaction is the key issue. The social interaction test between animals is effective to evaluate rat's sociality, anxiety, depression, schizophrenia. However, the social interaction test between animals does not have enough reproducibility due to the individual difference. Besides, this test system is quite difficult to measure as the animals are almost not controllable. Thus, we consider a robotic agent that interacts with animals provides new opportunities to perform the social interaction tests under more strict conditions. Consequently, the emergence of bio-inspired robots provides an effective approach to the behavior test of animal because of its controllability and measurability [4].

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In the past decades significant progress has been made on bio-inspired robots with good performance [5], [6], [7], [8], however, few animal-like robots could interact with animals [9], [10], [11]. Specifically, [10] presents general ideas on design and implementation of mini robots to study, model, and control mixed societies of animals and robots. In our research project, rats have been chosen as our experiment subject for numerous merits [12]. A rat-inspired quadruped robot was developed to study the rat's behavior recently [13], [14]. For instance, in [15], a rat-inspired legged rat robot was developed as an experimental tool to study social interaction between rats and robots. Although this rat robot can walk, trot, and stand, with similar postures and gestures as real rats, it is incapable of rat social behaviors such as rearing, sniffing, mounting and grooming. Thus, it is quite necessary to develop a biomimetic quadruped robot that better represents rat social behavior.

Therefore, aiming at social interaction test with rats [16], we previously developed a quadruped animal-like robot WR-1 (Waseda Rat No. 1) shown in Fig.1. As an improvement, a novel quadruped animal-like robot WR-2 (Waseda Rat No. 2) (shown in Fig.1) has been designed recently.

II. MODELING OF RATS MOTION AND WALKING

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 during walking or rotation. According to animal researchers, and also meet with the requirements of the interaction test, 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, in present research we put emphasis on the body miniaturization and the motion performance improvement of rat-inspired robot.

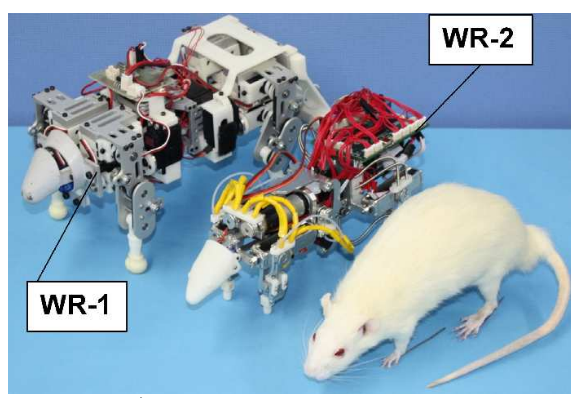


Fig.1. Shape of Animal-like Quadruped Robot WR-1 and WR-2 comparing with an adult rat:WR-1 is not a good imitation of rat owing to its bigger shape;WR-2 has further miniaturization and better imitation of rat shape.

A. Rat-inspired Design Concepts

To naturally interact with a rat, the dimension scale of WR-2 should be similar to that of an adult rat. Besides, it should possess similar mobility as a real rat in several social interactions such as chasing, rearing, grooming and mounting. Therefore the design concepts of WR-2 are mainly based on body characteristics and skeleton structures of the mature rat.

From the observation of rats and the reference to biological literatures [16], [17], the biological data of rats is available as shown in Table I. The body dimension of the robot needs to be designed in the range of these data.

TABLE I
THE BODY DIMENSION AND WEIGHT OF AN ADULT RAT

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

In order to act the similar social behaviors as rats, the motion mechanism of the robot was designed on the basis of the behavioral model of the rats shown in Fig.2. Besides limbs, the social behaviors of rats are mainly implemented by the neck and waist. In view of moving range, if the rotation and rearing can be realized, then the social interaction as grooming and mounting will be physically realizable. Therefore, according to rat anatomic pictures, the joint angle range of rats in the motion of rotation and rearing can be determined as shown in Fig.2. These angle ranges can be used as the key reference of robot joint design concepts.

B. Configuration of DOF

The DOF arrangement of a mature rat is experimentally obtained from the motion analysis. Walking motion of a rat is recorded by a video camera, and a stick diagram is obtained by visual analysis as shown in Fig.3. 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

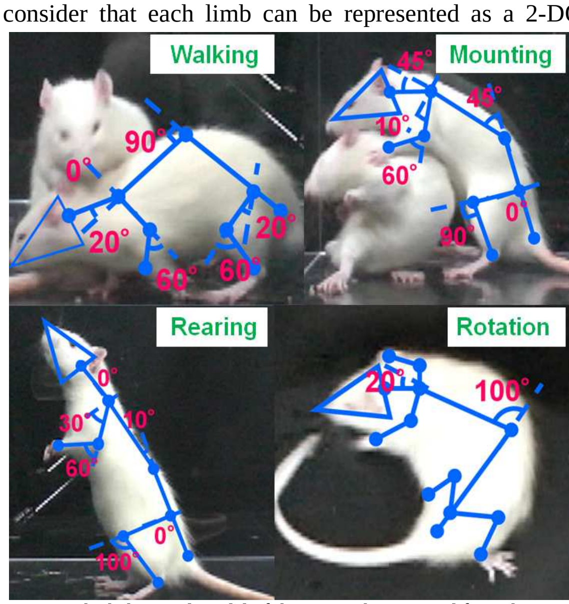


Fig.2. The behavioral model of the rat can be acquired from the analysis of single behavior and mutual interaction of rats.

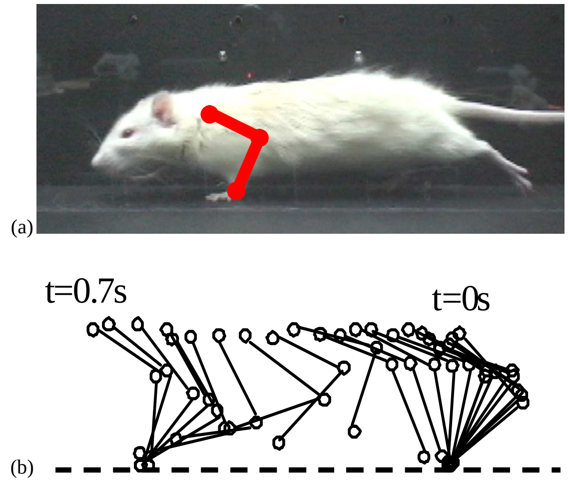


Fig. 3. Capture of the rat walking gait in x-z plane: a) The rat is walking through a resin cover plate at a speed of 0.33m/s. It is recorded by a video camera. b) Analysis of the rat walking gait captured 30 ms once.

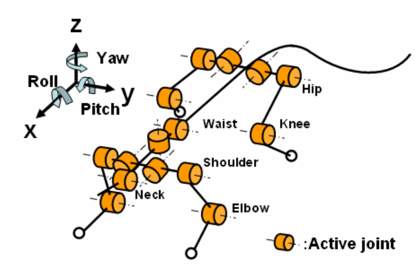


Fig.4. From the behavioral model and walking gait of an adult rat, the DOF arrangement and kinematical model of WR-2 is designed

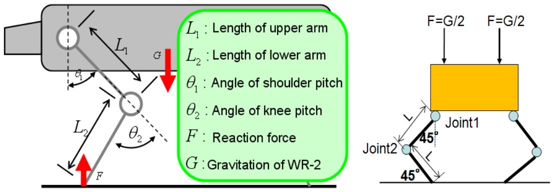
manipulator, a roll and pitch at the shoulder/hip, a pitch at the elbow/knee. In addition, rats have a flexible spine, and they can bend their body when they rear or groom by limbs. We consider these motions can be represented by a 2-DOF waist joint, a pitch and a yaw. Via this kind of motion and kinematical analysis, we consider that the muscle skeleton structure of the mature rat can be represented by the kinematic model as depicted in Fig.4.

III. Design of a Quadruped Animaloid Robot

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 Fig. 5 (a).

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 Fig.5 (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 $F = G/2$, $L = L1 = L2$, 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



(a) (b)

Fig. 5. (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.

the limbs. As the rearing and rotation is 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

According to section II.B, 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 Fig. 6, 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.

As shown in Fig. 6, only the shoulder roll is directly driven by the DC motor. The shoulder pitch and the elbow pitch are driven by the DC motors via the wire and outer-tube connection mechanisms as depicted in Fig.7. The DC motors 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.

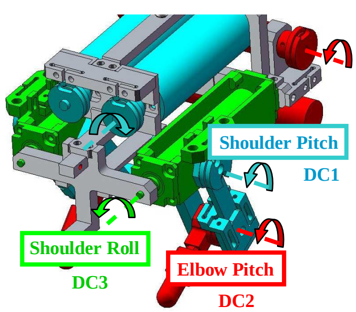


Fig. 6. Illustration of the mechanical design of the left arm. It consists of 3 DOF: roll and pitch of the shoulder joint and pitch of the elbow joint. The three DC motors are assembled in the body via wire and outer-tube driving mechanism to actuate corresponding joints.

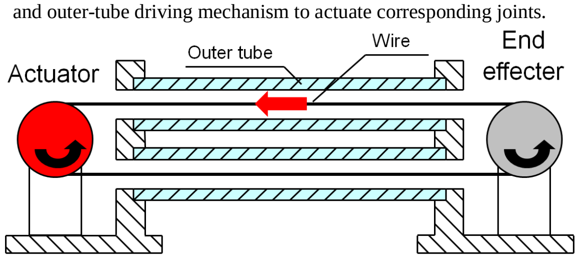


Fig.7. Wire and outer-tube driving mechanism: the wire is fixed at the actuator and the output object. The length of the tube is constant. As the tube is flexible, the actuator can be placed without many constraints.

TABLE II SPECIFICATION COMPARISON

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

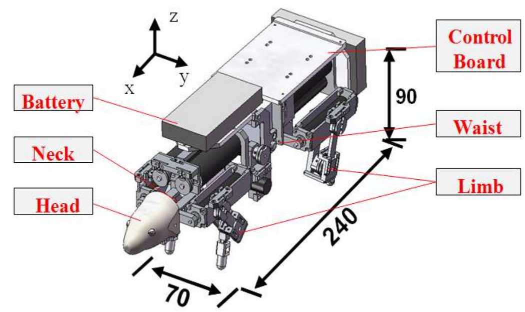


Fig. 8. Over view of WR-2 shows that the dimension and shape of this robot is quite similar to an adult rat.

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.

Resultingly, the main specifications of WR-2 have been designed as shown in Table II, while the interrelated specifications of an adult rat and WR-1 are listed as comparisons.

Finally, the whole hardware of WR-2 has been designed as shown in Fig. 8, based on the design concepts described previously.

IV. 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 Fig. 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.

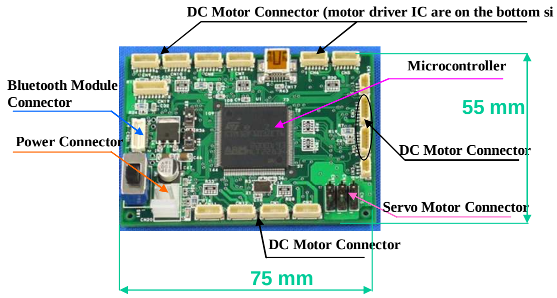


Fig.9. Controller circuit board of WR-2, a microcontroller, that is STM32F103ZE6T and 6 motor drivers (each drives two DC motors) are embedded in this circuit board.

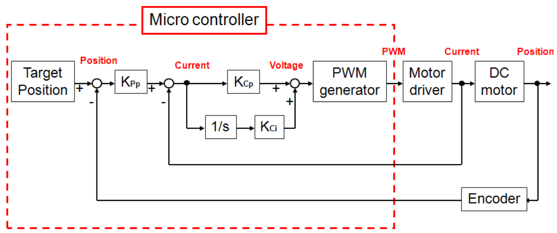


Fig. 10. Control flow chart, position feedback control (K_{Pp}: position proportional gain) and current feedback control (K_{Cp}: current proportional gain, K_{Ci}: current integral gain) has been used to accurately control the DC motors.

Angle of each DC motor is controlled with the position servo control as demonstrated in Fig. 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 [18] 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 Fig.11 [19]. 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 follows:

$$\sum_{i}^{AllParticles} m_i(r_i - r_P)\times(\ddot{r}_i - G) - \sum_{k}^{AllPoints}[(r_{Fk} - r_P)\times F_k + M_k] + T = 0 \quad (1)$$

In the Eq. 1, T denotes the total torque act on the point p. r_{Fk} the position vector of the actuation point by the kth external force or external moment. F_k, M_k the kth external force and external moment which act on the point k respectively.

From Eq. 1, when the point p is considered to be ZMP, we can set $T = 0$. Thus, the following ZMP formula is obtained. While r_{ZMP} denotes the position vector of the ZMP.

$$\sum_{i}^{AllParticles} m_i(r_i - r_{ZMP})\times(\ddot{r}_i - G) - \sum_{k}^{AllPoints}[(r_{Fk} - r_{ZMP})\times F_k + M_k] = 0 \quad (2)$$

Furthermore, if the relative motion is taken into account and the external forces are ignored, the ZMP formula based on the moving coordinate system $\bar{O} - \overline{XYZ}$ linked with the particle i can be derived as in Eq. 3.

$$\sum_{i}^{AllParticles} m_i(\bar{r}_i - \bar{r}_{ZMP})\times[(\ddot{\bar{r}}_i + \ddot{\bar{Q}} - \bar{G} + \dot{\bar{\omega}}\times\bar{r}_i + 2\bar{\omega}\times\dot{\bar{r}}_i + \bar{\omega}\times(\bar{\omega}\times\bar{r}_i)] - \sum_{k}^{AllPoints}[(r_{Fk} - r_{ZMP})\times F_k + M_k] = 0 \quad (3)$$

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

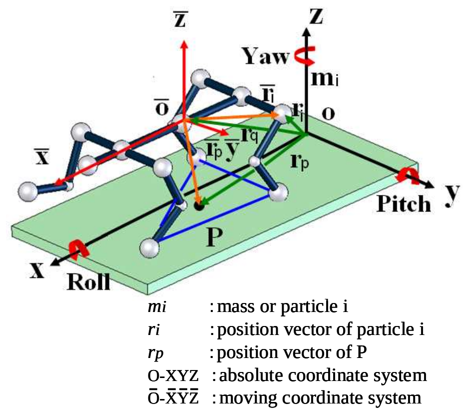


Fig. 11. Definition of coordinate systems and vectors

C. Walking Pattern Generation

Quadruped walking pattern generator was developed based on the walking algorithm described in section IV.B. As shown in Fig.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.
(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 in section IV.B.
(4) Then use the compensatory torso trajectory calculated in step (3) to generate walking pattern.
(5) Compute the moment errors e_M of planned ZMP trajectory, repeat the steps from (2) to (4) till the moment errors is less than the prescribed error (that is $e_M < \varepsilon_M$).
(6) Walking pattern generation and data output: all joint angles that are computed by using inverse kinematics

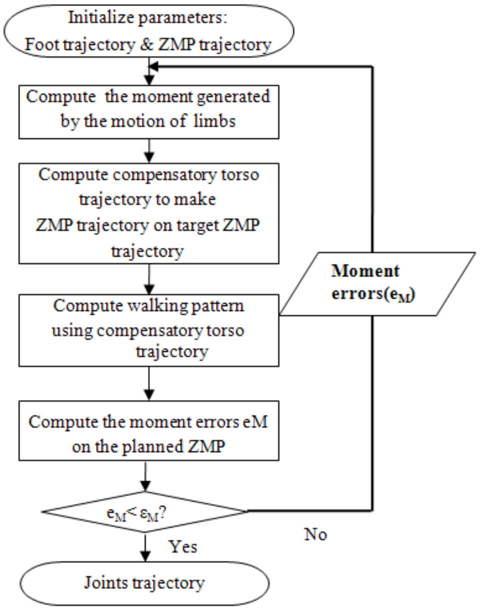


Fig. 12. Iterative algorithm for generating quadruped walking pattern.

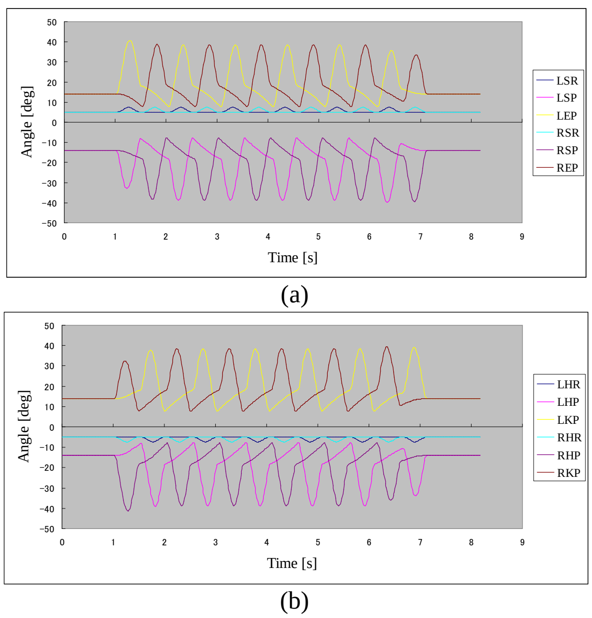


Fig. 13. Trot patterns of WR-2: a) Joint patterns of the arm: LSR, LSP, LEP, RSR, RSP and REP denote left shoulder roll, left shoulder pitch, left elbow pitch, right shoulder roll, right shoulder pitch and right elbow pitch respectively; b) Joint patterns of the leg, LHR, LHP, LKP, RHR, RHP and RKP denote left hip roll, left hip pitch, left knee pitch, right hip roll, right hip pitch and right knee pitch respectively.

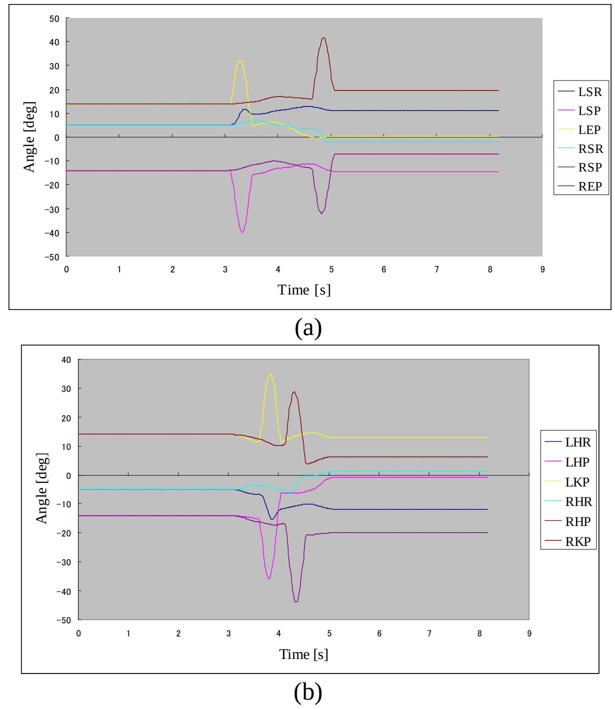


Fig.14. Rotation patterns of WR-2: a) Joint patterns of the arm b) Joint pattern of the leg. (The meanings of abbreviated letters of each line are the same as Fig.13.)

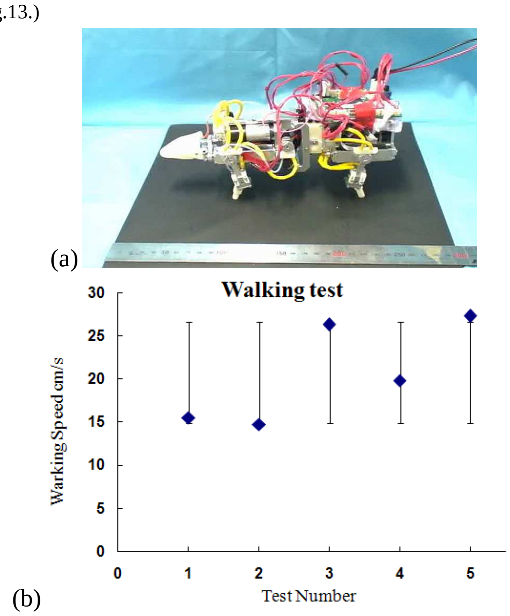


Fig. 15. (a)Walking speed test of WR-2 (b) Experimental results of the walking speed of WR-2

based on the foot and torso trajectory are output as time-line data. Finally, these data is turned into instructions to the DC motors.

According to the pattern generator narrated previously, the trot and rotation pattern of WR-2 have been generated as shown in Fig.13 and Fig.14.

V. Performance Evaluation and Experimental Setup

As the performance evaluation experiment, walking speed test of WR-2 has been conducted. The experiment condition is illustrated in Fig.15 (a), during each test, measure the distance and elapsed time, then the walking speed can be calculated. Five tests has been implemented, all the walking speed data are available as shown in Fig.15 (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.

VI. Conclusions and Future Works

In this research, a novel quadruped animaloid robot WR-2 for behavior analysis of rats has been developed.

WR-2 is much more similar to an adult rat in shape and dimension than its former version WR-1.

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 future research, we would like to stress the improvement of motion stability and robustness of WR-2.Fourthermore, we will start to perform experiments using WR-2, collaborating with animal psychologists and pharmacologists. As shown in Fig.16, we have established an automatic experimental system to measure the behavior of a rat using robots. Here, we will conduct the social interaction test described in section I using quadruped robot WR-2 that interacts with a rat. In duration of 10 minutes, the number of social interactions such as chasing, rearing, grooming and mounting between WR-2 and the rat will be measured in the automatic experimental system. From these experimental results, we can evaluate rat's anxiety [20] quantitatively. The validity of new psychotropic drugs can be evaluated using this methodology. For example, divide the disorder model rats into two groups, one group rats are given psychotropic drugs and the other group rats are not given any drugs. Make these disorder rats one by one do social interaction test with WR-2, if these rats that are given drugs behavior much more actively than those rats not given drugs, they will be thought to be return to health, and this new developed drug can be considered as effective to treat mental disorder.

For much further work, we would like to work on further miniaturization, a lightweight body and better similarity of rat appearance. On the basis of society interaction tests with WR-2, the establishment of a more optimal experiment system and the improvement of the body structure will be endeavored. We would like to do this, while taking into further consideration in the influence that the imitation of the rat shape and the reproduction of social behaviors has on real rat animals.

VII. Acknowledgements

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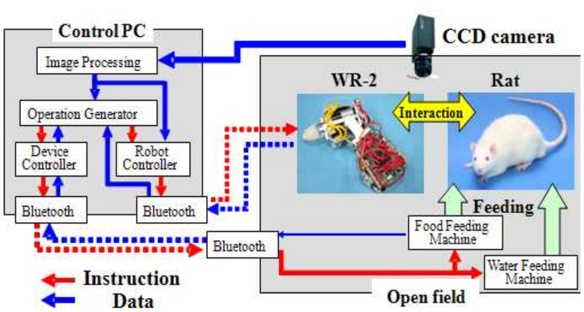

Fig. 16. Experimental setup. Interaction experiments between a robot and a rat are performed in an open-field. The robot and other equipments are controlled automatically by the PC.

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