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Locomotion Transition Scheme of Multi-Locomotion Robot

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1. Introduction

There are researches aiming to give a high environmental adaptability to robots. Until now stable locomotion of robots in complex environment such as outside rough terrain or steep slope has been realized [1–7]. Locomotion in the most of researches adapted to complex environment has been realized by single type of locomotion form. On the other hand, we have proposed Multi-Locomotion Robot (MLR) that can perform several kinds of locomotion and has high mobility as shown in Fig. 1 [8]. By using MLR, we have realized independently biped and quadruped walking, brachiation, and climbing motion so far [9–15]. Next research issue of MLR is to develop a systematic transition system from one locomotion form to the other.

Aoi et al. proposed transition motion from biped to quadruped walking by changing the parameters of the nonlinear oscillator and conducted experimental verification [16, 17]. These works focus on realization of a stable motion transfer and the transition according to external environment has not been discussed. Meanwhile, Asa et al. discussed the dynamic motion transition using the bifurcation of control parameters and realized motion transition between biped and quadruped walking [18]. These conventional researches aimed to realize a motion transfer between biped and quadruped walking. The transition motion of control system is constructed by using the Central Pattern Generator (CPG); the motion transfer of is realized by attractor transfer mechanism.

On the other hand, we aim to select suitable motion pattern for robots based on external environment and internal state of the robots and realize motion transfer from current motion to the other. In this chapter, we focus on biped and quadruped walking as motion patterns and report the suitable motion selection between biped and quadruped walk considering the walking stability and efficiency. Motion and recognition uncertainty is focused as factors to effect a realization of walking; then walking stability is evaluated from stability

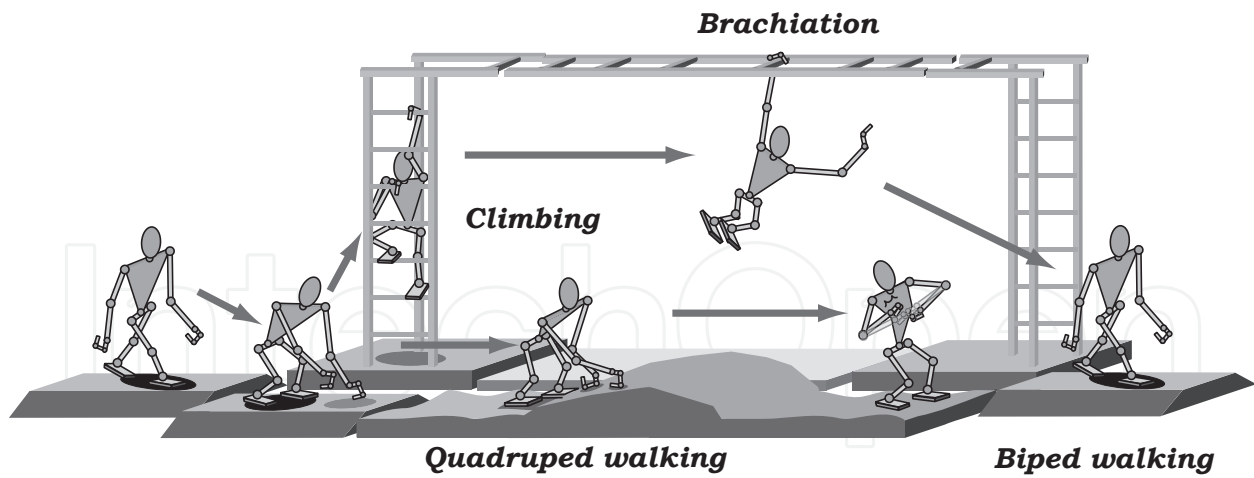


Figure 1. Concept of Multi-Locomotion Robot

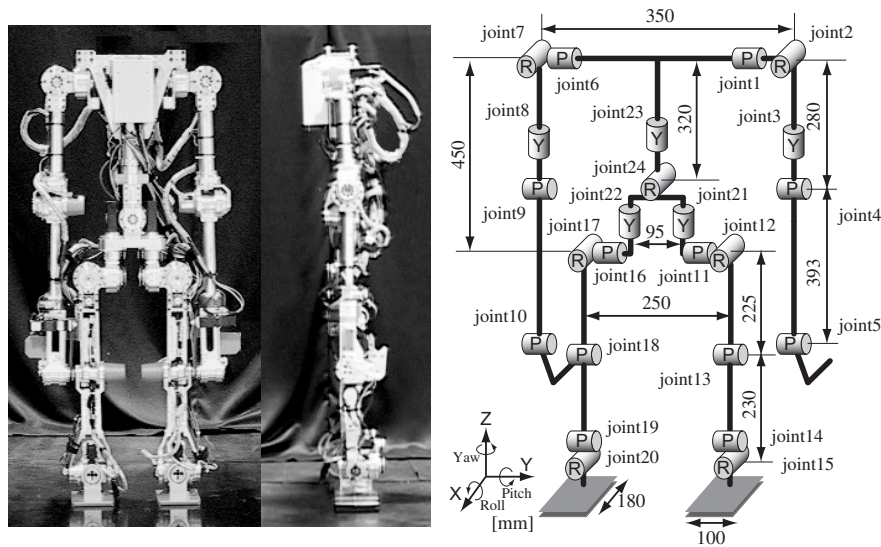


Figure 2. Gorilla robot III

evaluation parameters that have multiple uncertainties. Since dimension or class of the stability evaluation parameters that have uncertainty are different and the parameters cannot be used with uniformity, the parameters are integrated into the risk of falling down as the belief with Bayesian Network. The internal model to select the optimized motion pattern that minimizes falling down risk and maximizes the transfer efficiency is designed. Finally suitable locomotion selection between biped walking and quadrupedal walking is experimentally realized.

2. Multi-locomotion robot

2.1. Gorilla robot III

Multi-Locomotion Robot is a novel bio-inspired robot which can perform in stand-alone several kinds of locomotion such as biped walking, quadrupedal walking, and brachiation. We

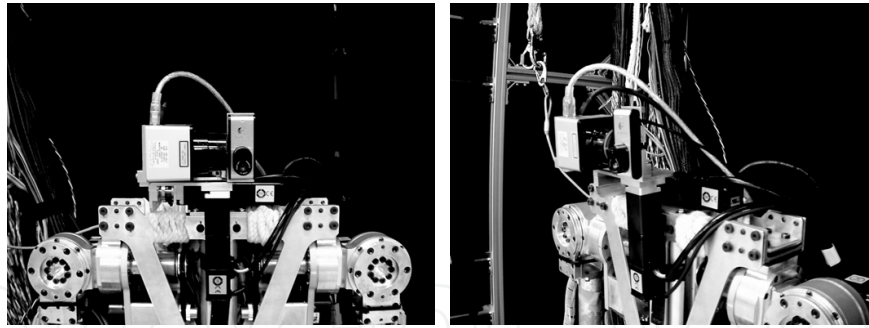


Figure 3. Laser range finder

built and developed Gorilla Robot III as a prototype of Multi-Locomotion Robot [8]. Overview and link structure of Gorilla Robot III is shown in Fig. 2. Its height is about 1.0 [m] and weight is about 24.0 [kg]. The mechanical structure is designed as follows: 6 DOF leg, 5 DOF arm, 2 DOF lumbar. Each joint is actuated by AC servo motor. Computer, AD/DA board, counter board, and power are set outside the robot.

As a sensor for recognition of slope, a laser range finder is installed at the neck of the robot (see Fig. 3). Its angular resolution is 0.36 [deg], scan angular range is 240 [deg], scan time is 100 [ms], and maximum range of detection is 4.0 [m]. The rotation axes of motors are pitch and yaw axes. In addition a web camera is also installed next to the laser range finder.

2.2. Locomotion mode

In this chapter, we model the robot as a 3D inverted pendulum same as the work for biped walking [19]. The supporting point of the pendulum is assumed to be point-contact. Then, only the heeling force f and the gravity act on Center of Gravity (COG). In this chapter, we use crawl gait as a quadruped walking [14]. In this gait, the idling leg changes, left rear leg, left front leg, right rear leg, and right front leg, in that order. It is designed in order that three feet always contact the ground, COG moves within the triangle which is formed by the three supporting feet. The transition from biped to quadruped posture is made keeping static balance. Before transiting the posture between biped and quadruped stance, the robot stops walking.

3. Locomotion stabilization

3.1. Internal model

In order to realize a robust robotic locomotion in any environment, two abilities are required: planning of the suitable motion based on the recognition of moving environment, and evaluation of generated motion. Then we propose the internal model based on a prediction and feedback as shown in Fig. 4.

Prediction for locomotion plans the locomotion form based on environmental information. Environmental information is sensed by a laser range finder; then the robot determines the suitable gait for the environment. In this research, biped and quadruped walking is focused as the gaits. The robot selects biped walking in the environment that is easy to walk such as flat

terrain. Meanwhile the robot selects quadruped walking in the environment that is difficult to walk in biped state such as slope or rough terrain. Also, the robot plans the walking steps and landing position of the selected gait based on recognized terrain. Previously, we designed this prediction for locomotion [20].

The feedback for locomotion evaluates walking stability based on internal condition of the robot. In this chapter, we propose the method of estimating the risk of falling down using Bayesian Networks (BN). In estimating the risk, we set "Robot Model Reliability (Reliability of Internal states)" and "Environmental Model Reliability (Reliability of External dynamics)". Reliability of a robot model shows how far difference between reality motion and locomotion algorithm is, or physical abilities of robot. For example, if the robot has motor trouble, this is low and the risk of falling down is high. Reliability of an environmental model shows how accurately a robot recognizes environment. If robots move in dark, it does not get information of environment, so this parameter is low and the risk of falling down is high. In biped and quadruped walking, the robot evaluates both reliabilities, estimate the risk of falling down and attain an optimum gait adapting to the environments or the conditions. This feedback for locomotion is explained in the next section.

3.2. Stabilization based on internal conditions

3.2.1. Estimation of falling down risk

In this chapter, we consider the uncertainty caused by motion and recognition as the factor of realization of locomotion. Approximation of motion algorithm is pointed out as uncertainty caused by motion. Most robots have models to simplify calculating dynamics. Thus, this gives robot systems uncertainty because there are difference between a reality robot shape and a robot model. Uncertainty caused by recognition is accuracy of sensors, effective ranges of sensor or abstraction of environment. There are many kinds of uncertain parameters which have various dimensions, so it is difficult to deal with them uniformly. Then, these parameters are integrated into the risk of falling down as belief with Bayesian Network. The Bayes theory assumes that parameters have distributions individually, and posterior probability is induced formally by conditional probability. Bayesian Network is the model which describes relations

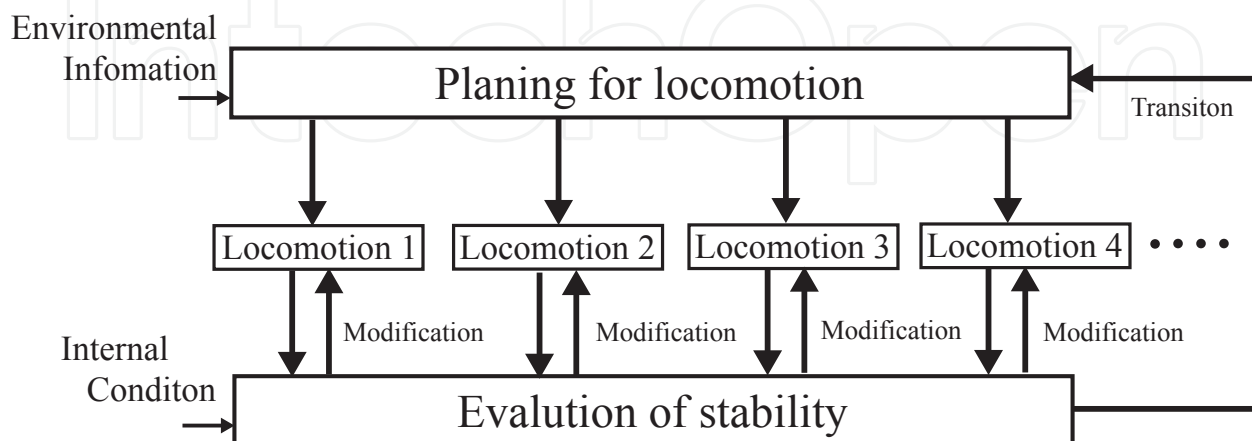


Figure 4. Locomotion stabilization scheme

among phenomenon using probability. We describe the causality between the risk of falling down and the uncertain parameters.

In this research, Bayesian Network shown in Fig. 5 is used to estimate the risk of falling down. First, Bayesian Network estimates Robot Model Reliability "R" and Environmental Model Reliability "E". Reliability of a Robot Model R show how ideal the robot motion is,

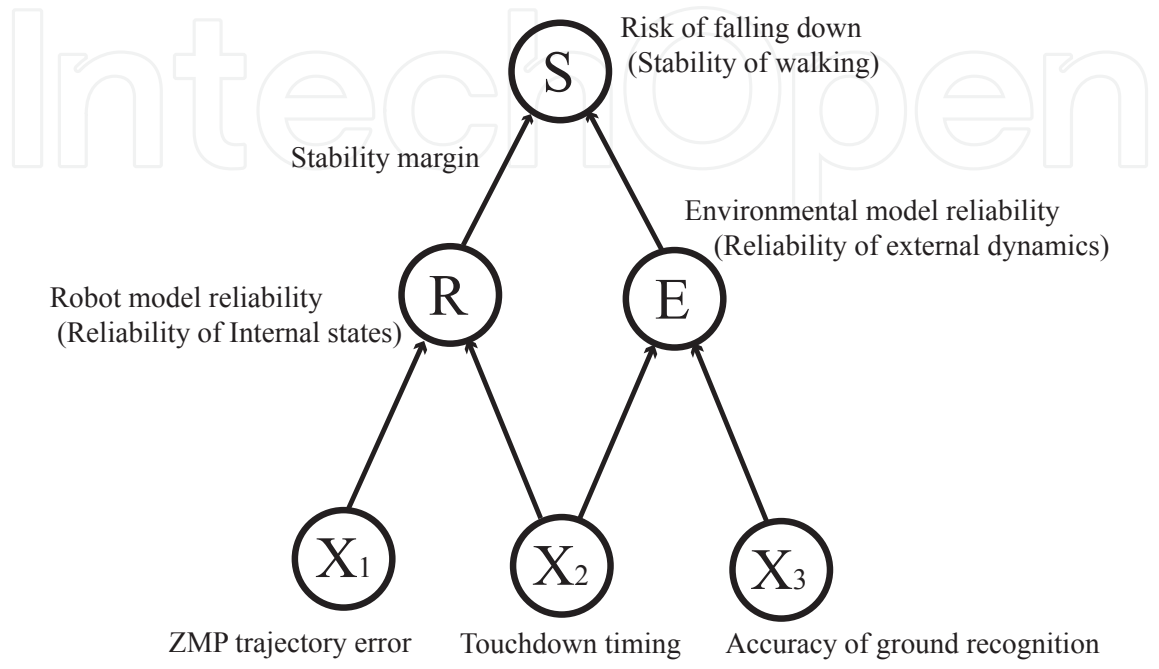


Figure 5. Bayesian Network for locomotion stabilization

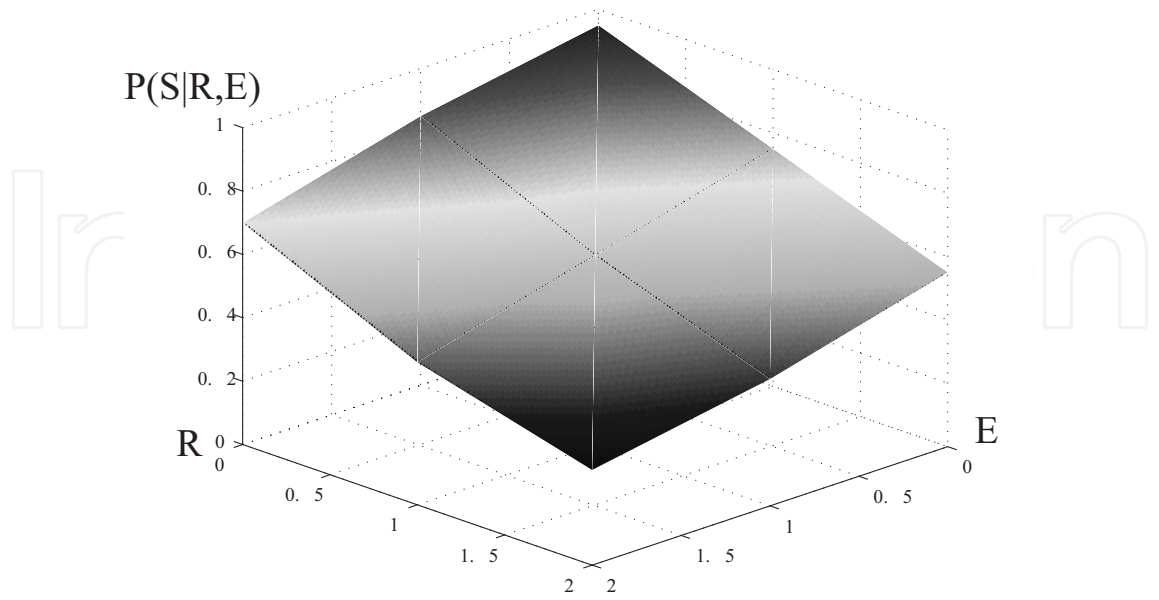


Figure 6. Probability for Biped Walking

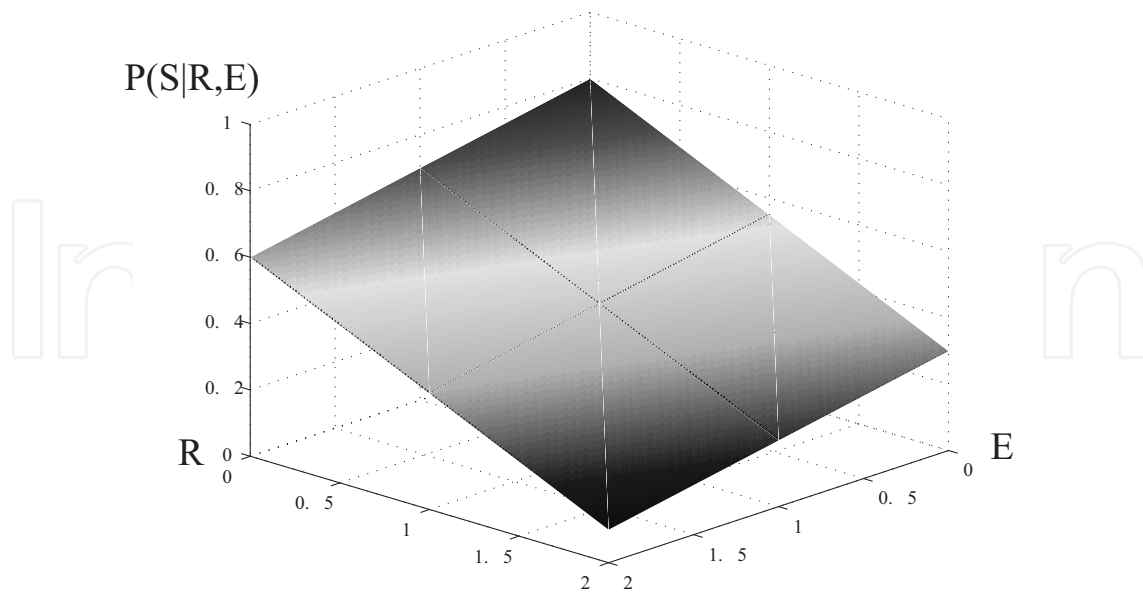


Figure 7. Probability for Quadruped Walking

and describes the capacity of moving. Reliability of an Environmental Model E is an index which shows how correctly the robot perceive the dynamics between the environment and the robot. Secondly, R and E are induced the risk of falling down “ S ”. “ $S = 1$ ” shows falling down, and “ $S = 0$ ” shows not falling down. Probability variables R and E have classes 0, 1, 2 in more reliable order. Then conditional probability $P(S | R, E)$ reflects the performance of the robot, and the designer arranges this probability subjectively. Probability distribution of biped walking is different from quadruped walking so that $P(S | R, E)$ of biped walking is higher than quadrupled one. Fig.6 and Fig.7show $P(S | R, E)$ of biped walking and quadruped walking respectively. The evaluating parameters X_1, X_2, X_3 shown below are observed at real time. Then probability variables from 0 to 4 based on uncertainty which the parameters have input the Bayesian Network. When the probability variable is 0, the situation is most stable. The calculation of Bayesian Network uses the enumeration method shown by (1).

$$\begin{aligned}
 P(S = 1) &= \frac{\sum_{R=0}^2 \sum_{E=0}^2 P(S = 1, R, E)}{\sum_{S=0}^1 \sum_{R=0}^2 \sum_{E=0}^2 P(S, R, E)} \\
 &= \frac{\sum_{R=0}^2 \sum_{E=0}^2 P(S = 1 | R, E)P(R | X_1, X_2)P(E | X_2, X_3)}{\sum_{S=0}^1 \sum_{R=0}^2 \sum_{E=0}^2 P(S | R, E)P(R | X_1, X_2)P(E | X_2, X_3)} \tag{1}
 \end{aligned}$$

The evaluating parameters X_1, X_2, X_3 are always observed, so each probability $P(X_1), P(X_2), P(X_3)$ is set 1.

3.2.2. COG trajectory error X_1

The position of the center of gravity is measured by the force sensor which the robot put on its four legs. In biped posture, outputs which come from the sixth axis force sensor makes ZMP. In quadruped posture, the center of gravity is calculated with the equilibrium of moments. Then the errors between the desired trajectory and the observed trajectory decides the probability variable X_1 .

3.2.3. Touchdown timing X_2

The touchdown timing shows differences between the landing and the ground surface actually. When the robot is thrown off balance, or when the recognition is inadequate and the ground is higher than measured point, then the touchdown timing is earlier than the planed timing. In the robot moving, the probability variable X_2 is renewed at every landing.

3.2.4. Accuracy of ground recognition X_3

This parameter evaluates the performance of the recognition which the robot has. This shows how much information the robot attain with some sensors, and how abstracted the environmental model which the robot has is. The laser range finder has effective ranges, so over this ranges there is much uncertainty. Then the two-dimension recognition and the approximate algorithm have the uncertainty.

3.3. Consideration of stability margin

The conditional probability $P(S | R, E)$ describes the influence which Reliability of a Robot Model R have with the Risk of falling down S . Then when the stability margin is enough large compared with the COG errors, the influence is little even if R goes down. In reverse, when the stability margin is small, R has a big influence on S . Therefore $P(S | R, E)$ is decided based on the stability margin. For example, a stability margin in biped posture is smaller than one in quadruped posture, so $P(S | R, E)$ in biped posture is larger than in quadruped posture.

3.3.1. Consideration of stability margin

The conditional probability $P(S | R, E)$ describes the influence which Reliability of a Robot Model R have with the Risk of falling down S . Then when the stability margin is enough large compared with the COG errors, the influence is little even if R goes down. In reverse, when the stability margin is small, R has a big influence on S . Therefore $P(S | R, E)$ is decided based on the stability margin. Thus, $P(S | R, E)$ is changed by designing the revised value of conditional probability $\Delta P(S | R, E)$ shown in Fig. 8 according to the stability margine as follows:

$$P(S | R, E) = P(S | R, E) + \Delta P(S | R, E), \quad (2)$$

$$\Delta P(S | R, E) = -\frac{2\Delta P}{k_{max}}k + \Delta P, \quad (3)$$

$$0 \leq k \leq k_{max}, \quad (4)$$

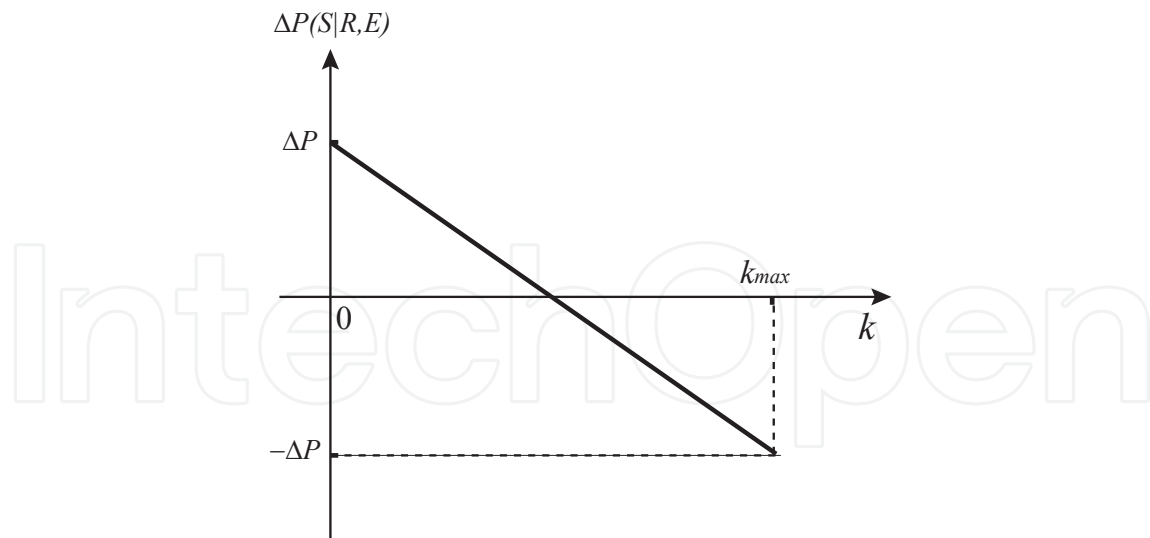


Figure 8. Revised Probability Value According to Stability Margin.

where ΔP is the maximum revised value of conditional probability and k_{max} is the maximum stability margin.

3.3.2. Switching of locomotion mode

The evaluating parameters X_1, X_2, X_3 are observed at real time, and the probability of falling down is estimated. The conditional probabilities used in Bayesian Network are arranged by the subjective judgments of the designer. Therefore, when the robot falls down, the probability of falling down is not always 1.0. So we pay an attention to the fluctuation of the probability. That is, when the robot move in biped posture and the risk of falling down increases, then it has the transition motion from biped to quadruped posture and go quadruped walking. Contrarily the risk decreases in quadruped walking, the robot stands up and go biped walking.

4. Experiments

4.1. Experimental conditions

In this experiment, the robot measures the landform with the laser range finder at starting point, and in walking, it get the gait based on the risk of falling down estimated by Bayesian Network shown in Fig. 9. When the risk is more than β (0.7) in biped posture, the robot squats to get quadruped posture. And when the risk is less than α (0.3) in quadruped posture, it standups. Then the robot in biped posture has three patterns of biped walking a_1, a_2, a_3 which have different efficiency. If the risk decreases, the robot get more efficient gait. In this research, this efficiency is the walking velocity, then a_1, a_2, a_3 are respectively 8.67, 6.67, 4.67[cm/sec] acquired by stride widths changed and the quadruped walking velocity is 3.00[cm/sec]. Both the standup motion and the squat motion take 10[sec] to action. Modifications of its gait are conducted in every walking cycle. The robot aims at minimizing the risk and maximizeing the efficiency all the time.

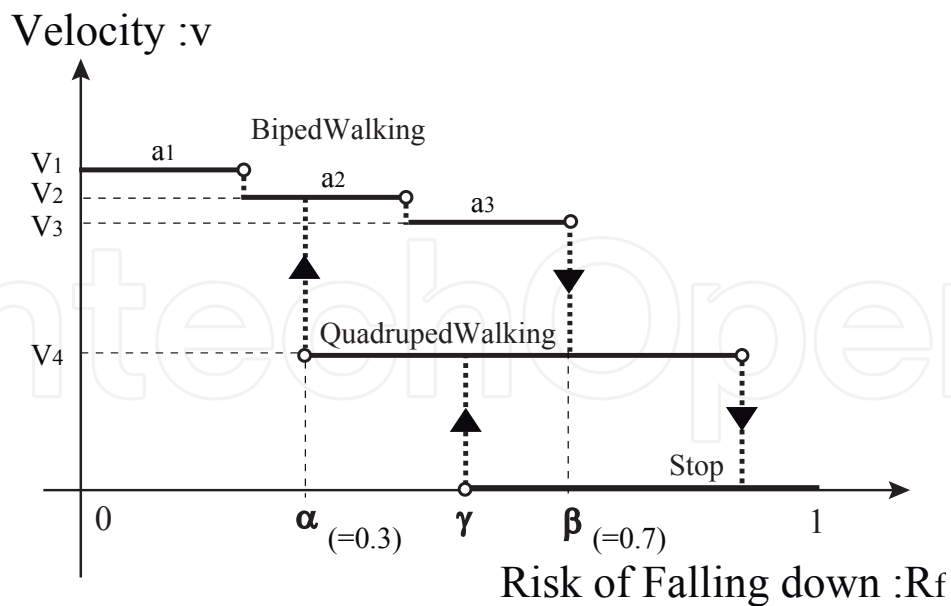


Figure 9. Velocity - Risk of falling down

4.2. Experimental results

4.2.1. Experiment 1: gait selection based on falling down risk (biped to quadruped)

In this experiment, the robot walks on rough ground. There are inequalities which have the maximum height, 5[mm]. This is not recognized by the robot on purpose. We confirmed whether the robot in biped posture changes the gait to quadruped mode because the risk increases.

Fig. 10 shows results about the COG trajectories come from the force sensors. And the COG trajectories induce X_1 shown in Fig. 11. Fig. 12 describes the probability variable X_2 . The numbers in these figures are the threshold to apportion the probability variable. In this experiment the node X_1, X_2 have 0, 1, 2, 3, 4 as the probability variables. When the probability variable is 4, the robot almost falls down. The node X_3 is always 0 because the robot move within the effective ranges of the laser range finder in this experiment. Thus, Fig. 13 is the risk estimated by Bayesian Network. In the transition motion, the risk is 0.0. We can see the transition caused by the risk increasing. Before the robot conducts a squat, the risk is more than β (0.7). And snapshots of the experiment is shown in Fig. 14.

4.2.2. Experiment 2: gait selection based on falling down (quadruped to biped)

The experiment 2 confirms the transition of locomotion form when the robot starts walking in quadruped state and is given shaking disturbances made by human. Fig. 15 shows the estimated risk of falling down derived from the same way in the experiment 1. The risk of falling down is set 0 during transition from quadruped to biped walking. The risk of falling down is temporarily increased due to the shaking disturbances from human. It is confirmed that the robot stop and selects biped walking as locomotion form after disturbances stopped and the risk is less than α (0.3). Fig. 16 shows the snapshots of the experiment 2.

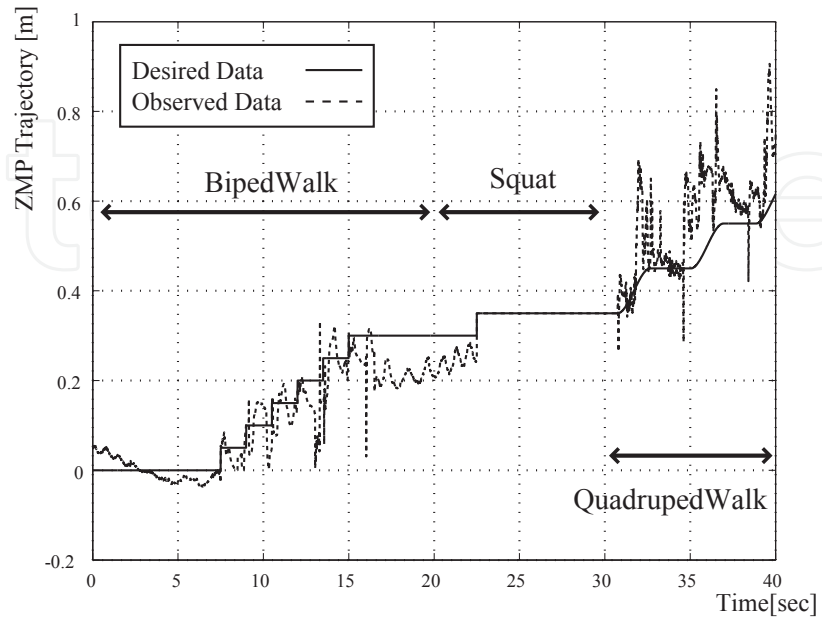


Figure 10. Comparison between desired and actual ZMP trajectory

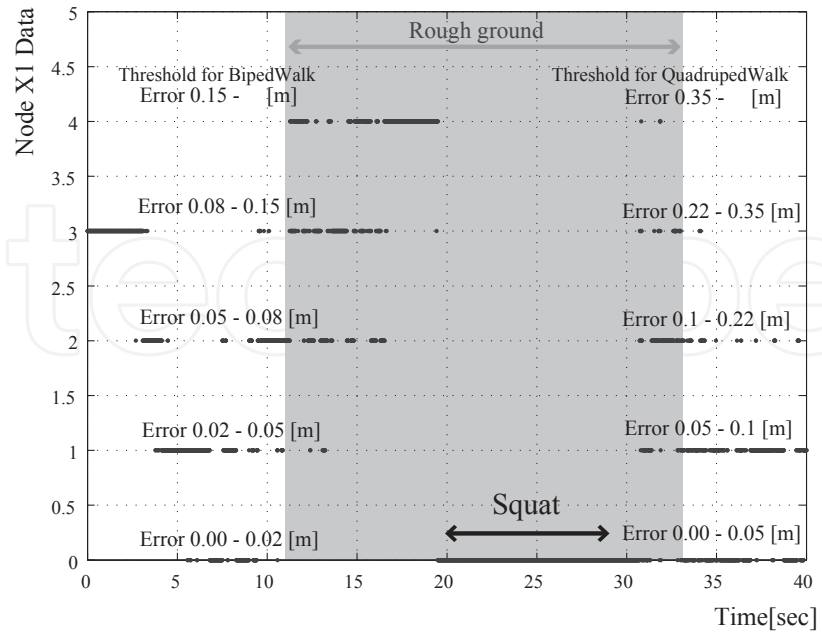


Figure 11. Experimental data of node X_1

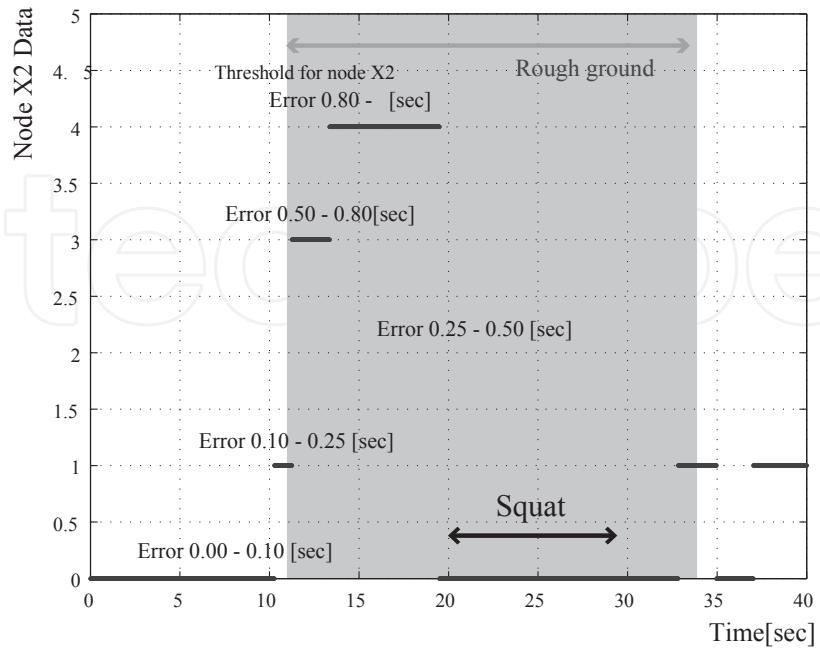


Figure 12. Experimental data of node X₂

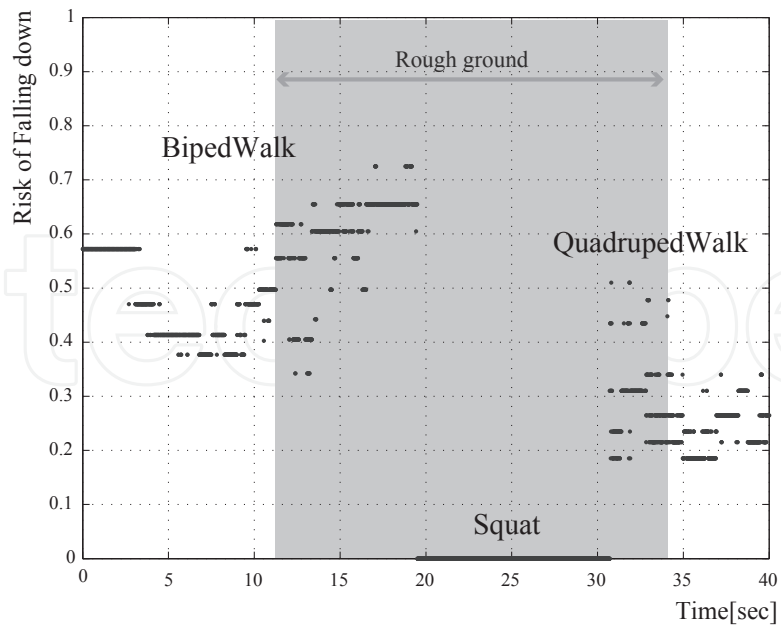


Figure 13. Risk of falling down (Experiment 1)

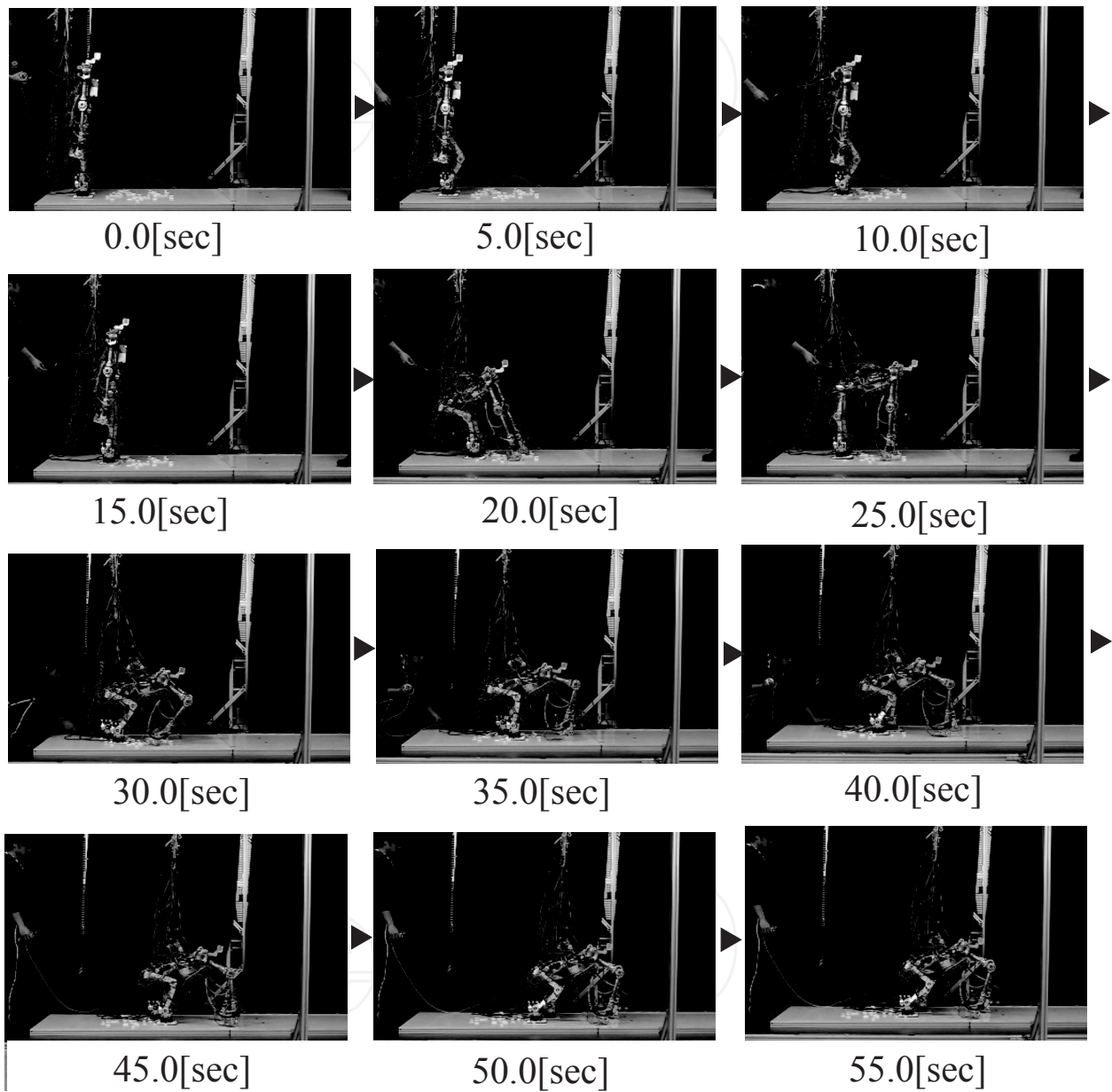


Figure 14. Snapshots of the experiment 1

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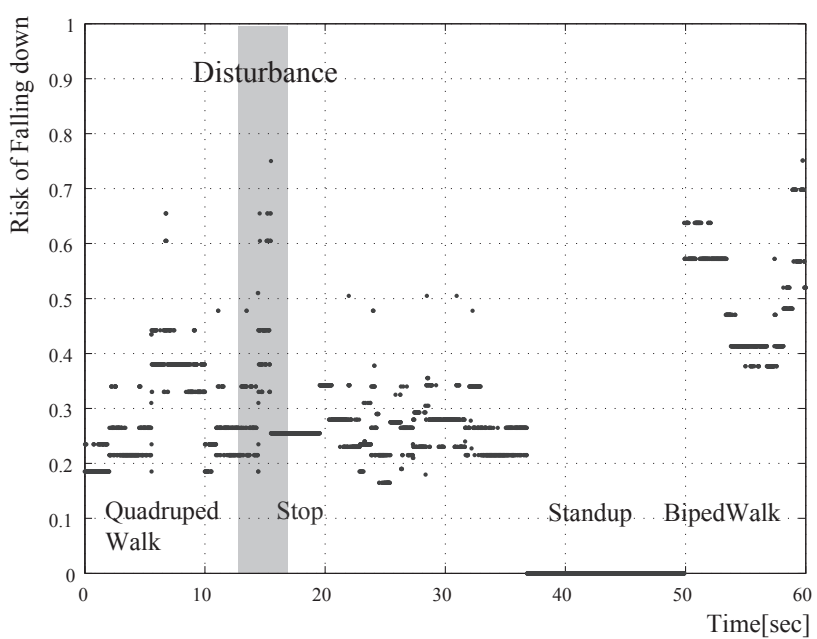


Figure 15. Risk of falling down (Experiment 2)

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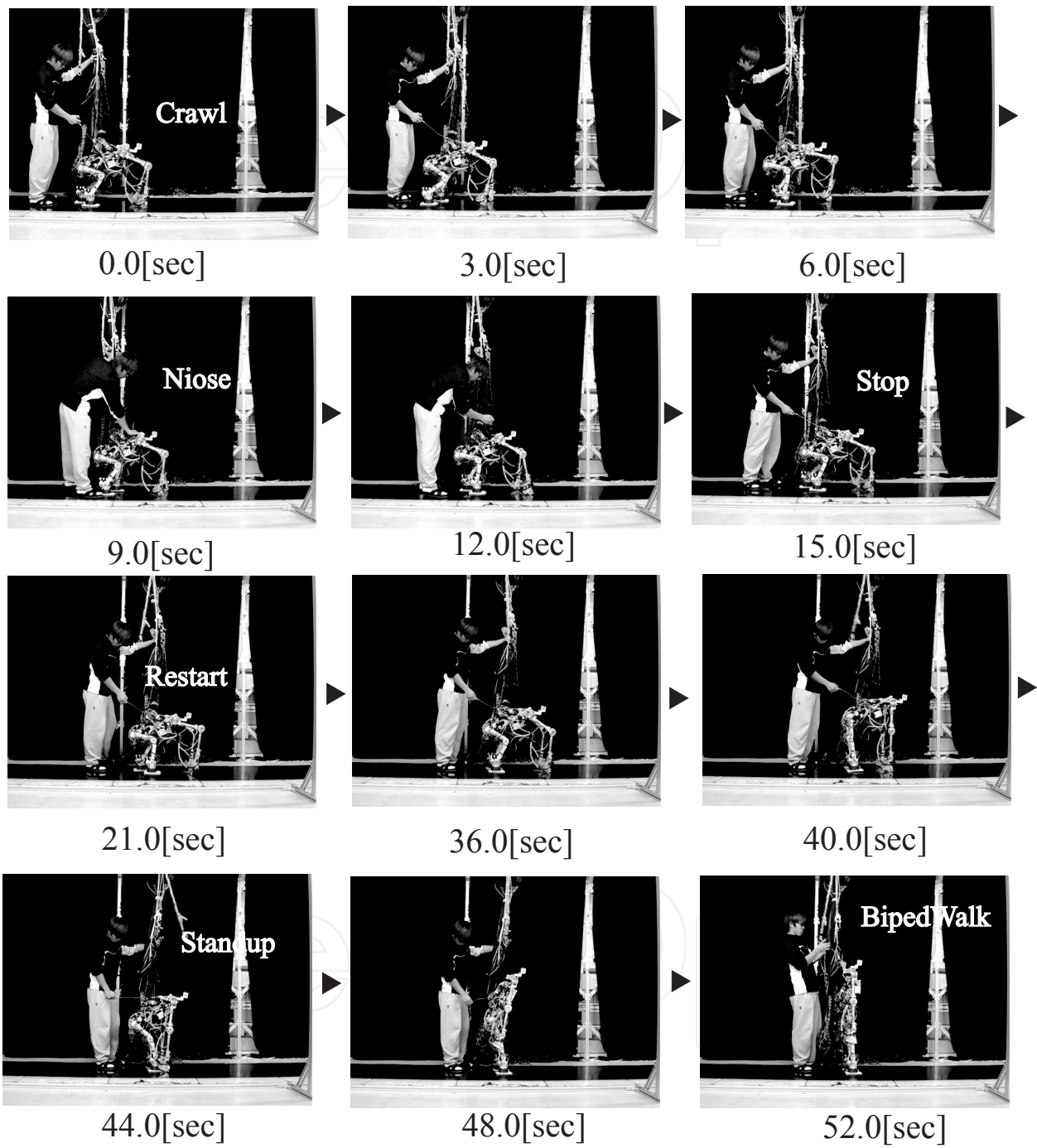


Figure 16. Snapshots of the experiment 2

5. Conclusion

This chapter firstly designed internal model composed of gait planning and stability evaluation. Next, the falling down risk is estimated by integrating stability evaluation parameters that has uncertainty using the Bayesian Network. Then we proposed the stabilization method that selects the suitable locomotion form according to the change of the falling down risk. Finally, the suitable locomotion transition is experimentally realized. Although we dealt with only biped walk and quadruped walk in this chapter, we will try to deal with other locomotion modes such as brachiation and ladder climbing for transition.

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