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Development of Quadruped Walking Robot TITAN-XII and Basic Consideration about Mechanics of Large Obstacle Climbing

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Quadruped walking robots are expected to be utilized on rugged terrain because of its high terrain adaptability. In order to establish the basis of the gait control of quadruped walking robots on large obstacles, we make simulation experiments about body rising motion. We investigate the appropriate foot positions and internal forces which eliminate negative power consumption, then optimize the motion in consideration of the actual characteristics of the installed actuators. Furthermore, a quadruped walking robot TITAN-XII is proposed and its design concept and system integration are discussed. Finally, the basic performance of TITAN-XII is demonstrated by a large step climbing experiment.

Keywords: *quadruped walking robot, active ankle mechanism, body rising motion*

1. Introduction

Quadruped walking robots have particular abilities as follows:

1) It has the minimum numbers of the leg to maintain static stability thus it can be lightweight and simple.
2) It can perform omni-directional locomotion with no slippage at the contact points.
3) It can work on rugged terrain by using the leg as arm with attaching the tool at the tip of the leg.

For these unique characteristics, it is suitable to do various works such as the transportation, construction and rescue operation on rugged terrain, and it has been researched for a long time [1]. Although the gait control on the flat plane and the sloping surface has been researched so far, it has not been researched enough about the gait control to travel on rugged terrain where legged locomotion is actually required.

In recent years, a small quadruped walking robot LittleDog has been developed as a part of DARPA project and it has been researched to go over the environment where undulations as large as the robot exist [2]. We also developed a large quadruped walking robot TITAN-XI for a steep slope operation whose weight is 7000[kg] [3]. However, applying the gait control of small scale walking robots like LittleDog to the large scale walking robots directly is suspicious because of the square-cube law (the mechanical strength is proportional to the area of cross section, whereas the mass is proportional to the volume). For example, the foot of LittleDog is sphere shape, but it is very difficult to apply it to a large scale quadruped walking robot directly due to the mechanical strength of the contact points. In case of TITAN-XI, the weight of the robot is compensated by the wire, that's why the gait control of TITAN-XI is not so different from the horizontal ground.

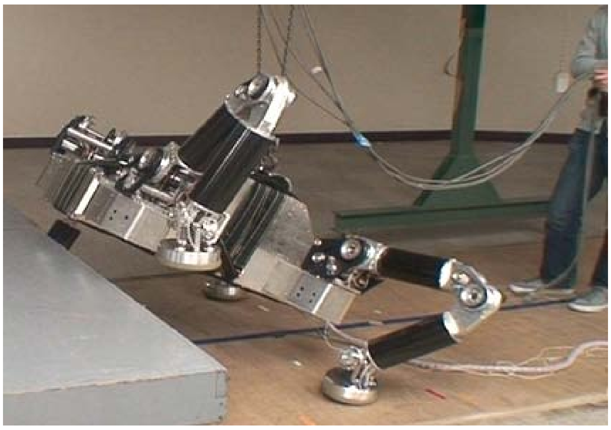

Fig.1 Overall view of TITAN-XII

Therefore, to develop a practical large walking robot in the future, it is important to develop an experimental model of the large scale quadruped walking robot and it is also necessary to confirm and solve the problem due to the size of the robot. Furthermore the gait control method to climb over large obstacles has not been researched yet as far as we know, so it is required to be investigated.

For above reasons, we have developed TITAN-XII for climbing large obstacles as shown in Fig.1. In this paper, we consider the basis of energy efficient obstacle climbing motion and optimize the body rising

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motion. Then we discuss the design and system configuration of TITAN-XII. Finally, we demonstrate basic performance of TITAN-XII by large step climbing experiment.

2. Basic Consideration of Energy Efficient Obstacle Climbing Motion

2.1 Energy characteristics of walking motion

When a quadruped walking robot with massless legs moves on the horizontal ground keeping the body height constant, the robot consumes zero power ideally, because the output forces are perpendicular to the velocities at each foot. Even if the main body does not consume power, there is a case that the leg actuator consumes power [4]. For example, the knee joint consumes positive power and the hip joint consumes negative power whose magnitude is identical to the positive power. Note that negative power consumption means the situation that actuators are supplied power from external work. However, walking robots cannot install regenerative systems in general because it is heavy and complicated, thus negative power consumption cannot be regenerated and dissipated as heat. Therefore, negative power consumption does not contribute to the walking motion. To eliminate negative power consumption, the concept of GDA(Gravitationally Decoupled Actuation) is proposed [4]. GDA is a concept to eliminate the negative power consumption by designing joint arrangement in order to generate only force or velocity. It is also investigated to achieve energy-efficient crawl gait by selecting appropriate posture satisfying the GDA condition [4].

In the case of large obstacle climbing, positive power consumption equal to the increase of potential energy is essentially required because the robot raises the body against the gravity. To the best of our knowledge, change of the power consumption in each joint during the motion essentially requires positive power consumption has not been investigated yet. For the first approach to investigate power consumption at each joint during large obstacle climbing, we analyze the body rising motion as shown in Fig.2 which is the simplest motion requiring energy consumption against gravity.

2.2 Mechanical energy consumption changed by various leg width

Leg width is one of the parameters to define the body rising motion. Here we calculate energy consumption when the robot raises its body quasi-statically 0.4$[m]$ where each leg moves from $H_0 = 0.3[m]$ to $H_1 = 0.7[m]$ at constant speed as shown in Fig.2. We use open-source physics library Open Dynamics Engine(ODE) in this simulation analysis [5]. In this simulation it is assumed that the simulation model has the same weight and size as TITAN-XII, and the weight of legs is negligible small. It is also assumed that each leg evenly supports 245[N] which is one-fourth of the weight of TITAN-XII. Leg width parameter Y is the horizontal length from joint2 to the foot placement normalized by Link2 length l. We discuss the case where Y is positive, because the posture where Y is negative is not practical due to less workspace and low stability. The robot keeps body posture parallel to the ground during the body rising motion, thus Joint1 does not consume power. Therefore we investigate the energy consumption of Joint2 and 3.

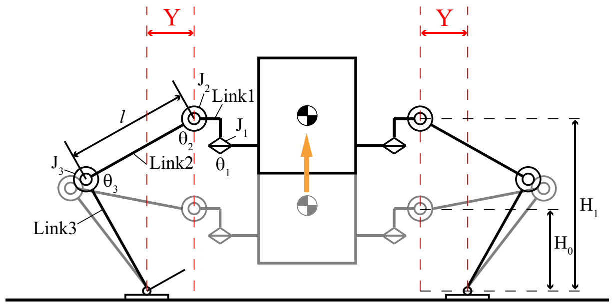


Fig.2 Body rising motion

Fig.3 shows mechanical energy consumption of Joint2 and 3. Note that mechanical energy consumption of Joint3 is devided into positive and negative energy consumption. It is assumed that negative energy consumption cannot be regenerated and we calculate total mechanical energy consumption of the robot from positive energy consumption. Fig.3 shows that negative energy consumption appears when the leg width Y is larger than approx. 0.95l, and the more Y increases, the more negative energy consumption increases. This is because the torque direction of Joint3 changes when Y becomes approx. 0.95l. Fig.4 shows the posture at Y is 1.18l where negative energy consumption was the biggest in this simulation. From this simulation, it was confirmed that negative power can be generated during the motion which essentially requires positive work and the foot should be placed appropriately to eliminate negative power consumption.

2.3 Mechanical energy consumption changed by generating internal forces

When the robot walks on rugged terrain, it is generally considered that the robot cannot always take appropriate posture in order to not generate negative power because of many reasons, for example, the condition of the environment and the limitation of reachable area of the leg, and so on. In this case, if internal forces are generated with satisfying friction

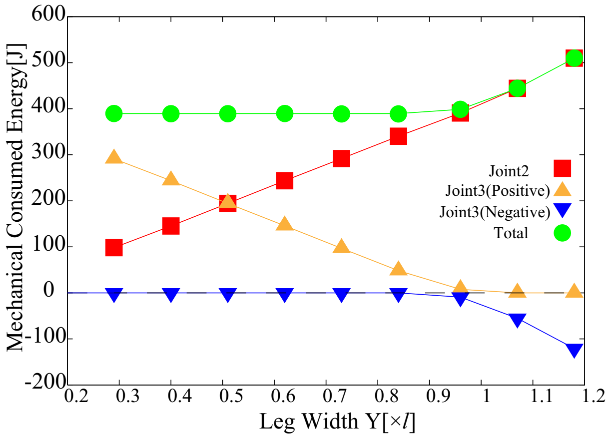


Fig.3 Energy consumption change by leg width

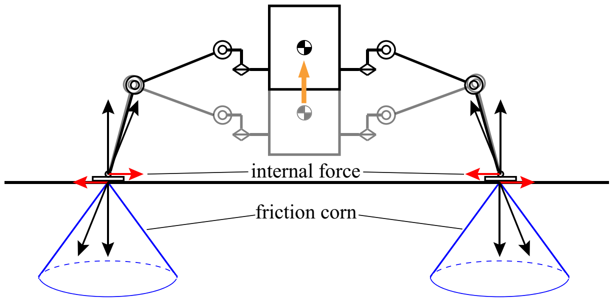


Fig.4 Body rising motion with horizontal internal force

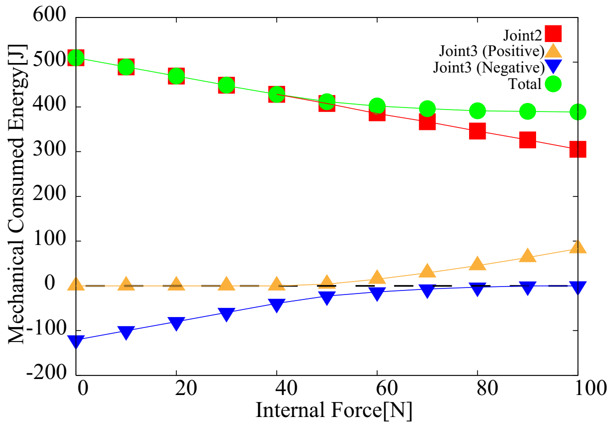


Fig.5 Energy consumption change by internal force

constraints as shown in Fig.4, the robot does not slip at contact points. Then the distribution of the joint torque changes because the direction of the output force of the leg changes, and the distribution of the joint power also changes.

We investigate change of energy consumption by changing the internal force at Y is $1.18l$ where negative power consumption was large at foregoing simulation. Same as the simulation in 2.2, it is assumed that each leg supports 245[N] equally in this simulation. It is assumed that the coefficient of friction is 0.4. Internal force generation can be changed from 0 to approx. 100[N].

Fig.5 shows mechanical energy consumption of Joint2, 3 and the whole robot. The more the internal force increases, the more the energy consumption at Joint2 decreases and at Joint3 increases. Finally in the case of generating 100[N] internal force at the foot, negative energy consumption is completely eliminated. This case is just described in Fig.4 and Joint2 torque becomes small and the sign of Joint3 torque changes compared to the case of no internal force. From above analysis and consideration, it was confirmed that negative energy consumption can be eliminated by generating appropriate internal force at the foot.

2.4 Consideration of actuator characteristics

So far, it was considered that actuators couldn't regenerate but its energy efficiency was 100%. However, in fact, the energy efficiency of actuators changes with operating velocity and torque. Thus it is important to drive actuators on high energy efficiency operating conditions in addition to eliminating negative energy consumption. We investigate energy efficient body rising motion with considering actual actuator as DC motor.

First, it is considered to clarify the model of DC motor. DC motor cannot be driven continuously over the heat threshold because of structural limits. By using equivalent circuit model of DC motor, this continuous driving range is represented as inside of a ellipse which is described by Eq.1.

$$\frac{R_a}{K^2}\frac{1}{\xi^2}\tau^2 + \frac{2R_a}{R_h}\tau\omega + \frac{K^2}{R_h}\left(\frac{R_a}{R_h}+1\right)\xi^2\omega^2 \leq \frac{2P_{\max}}{\sqrt{1+R_h/R_a}-1} \quad (1)$$

Here, joint torque τ, joint angular velocity ω, representing resistance of copper loss R_a, representing resistance of iron loss, windage loss etc. R_h, torque constant K, maximum output power $P_{\max}$, and reduction ratio of each joint ξ which is described in Table.1 are used(R_h is calculated from the maximum energy efficiency $\eta_{\max}$ and R_a which are described on a catalog[1]). If mechanical power consumption is positive, power consumption of DC motor is represented by the sum of mechanical output power and heat loss

[1]From R_a, $\eta_{\max}$(=92%), R_h is represented as follows: $R_h = \frac{4\eta_{\max}}{\sqrt{1-\eta_{\max}^2}}R_a$.

Table 1 DC motor parameters

$R_a[\Omega]$	1.16
$R_h[\Omega]$	667
K[Nm/A]	0.0603
$P_{\max}$[w]	150

described in the left side of Eq.1, and if mechanical consumed power is negative, power consumption of DC motor is represented by only heat loss. As Joint2 of TITAN-XII is driven by two DC motors, consumed power of one motor is calculated from joint angular velocity and torque and twice the power. Total consumed energy during body rising motion is calculated from consumed energy of 16 motors in total. Simulations in this section are analyzed by MATLAB.

Fig.6 shows the simulation result when the leg width y was changed from $0.2l$ to $1.0l$ and the body velocity 0.1 to 0.9[m/s]. Moreover, body rising motion was optimized by using the optimization toolbox of MATLAB. In this optimization, the heat limit condition which is expressed with Eq.1 and maximum angular velocity(=7000[rpm] which can be realized at applying maximum voltage to motors) are considered as constraint conditions. Through this optimization of body rising motion, it was derived that minimum consumed energy was 434[J], optimal leg width was $0.6l$, and body velocity was 0.69[m/s]. Optimal energy efficiency was 90.3% because the total potential energy increase is 392[J]. Fig.7 shows trajectories of DC motor operating points and image of optimal body rising motion. In Fig.7, each line means the same energy efficiency operating conditions of the DC motor and each value means energy efficiency of the line. $\eta_{\max}$ means maximum energy efficiency operating conditions of the DC motor on the angular velocity-torque plane. It is confirmed that Joint2 and 3 are always driven on relatively high energy efficiency operating conditions of the DC motor during the motion.

Through these considerations, body rising motion was optimized and a basic strategy to achive high energy efficiency of large obstacle climbing was derived as follows:

1) Eliminating negative energy consumption by taking appropriate leg posture and generating appropriate internal forces.
2) Then taking appropriate body velocity and generating foot force to drive actuators at high energy efficiency operating conditions.

3. Development of TITAN-XII

3.1 Leg Mechanism

3.1.1 Structure

It is desirable for the leg to have sufficient wide movable range to adapt to rugged terrain. To achieve this requirement, some quadruped walking robots with prismatic joints have been developed [1] [6]. However it requires long leg length to secure wide motion range and causes increase in weight and size of the robot. Thus 3DOF serial linkage mechanism is adopted to the leg mechanism of TITAN-XII, and Joint2 and 3 are provided with offsets to enlarge sufficient movable range from bottom side to upper side of the body. Fig.8 shows the structure of the leg and reachable area of TITAN XII, and Fig.9 shows the prototype of the leg.

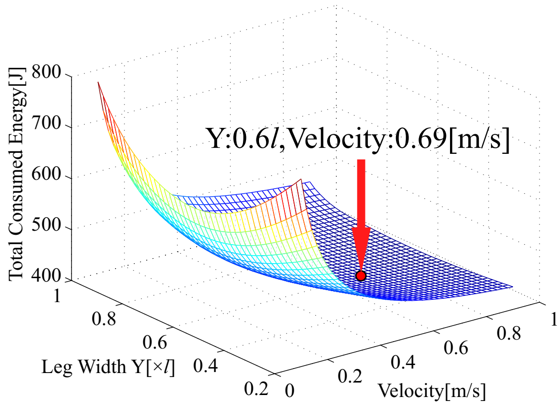


Fig.6 Energy consumption of the DC motors

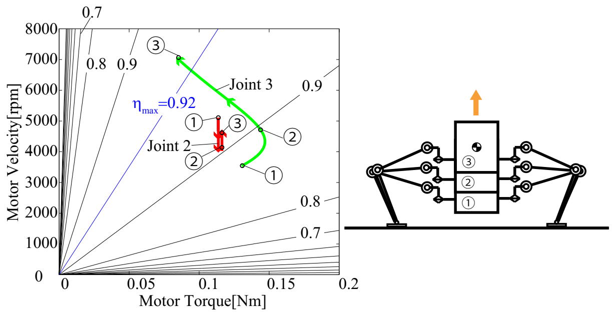


Fig.7 Trajectory of DC motor operating points

3.1.2 Driving system

To secure large stability, a insect type leg configuration is adopted to TITAN XII. In this case, Joint2 must support large torque due to the weight of the robot. When the robot travels on rugged terrain, it is required to change its body posture according to the ground shape, thus Joint1 must support some torque unlike the walking motion on the horizontal plane. Then Joint2 should output large power and Joint1 and 3 also should output appropriate power which are not larger than output power of Joint2.

For above reasons, one 150W DC motor(Maxon RE40:148877) is installed in Joint1 and 3 and two motors in Joint2. Harmonic Drive is used as main

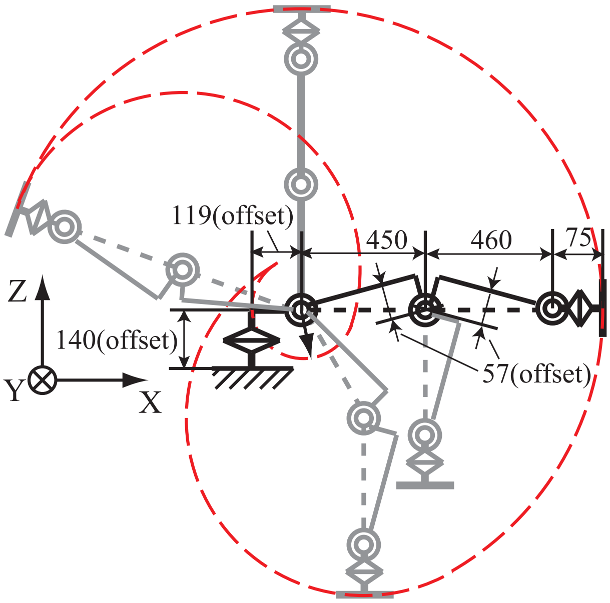


Fig.8 Workspace of the leg

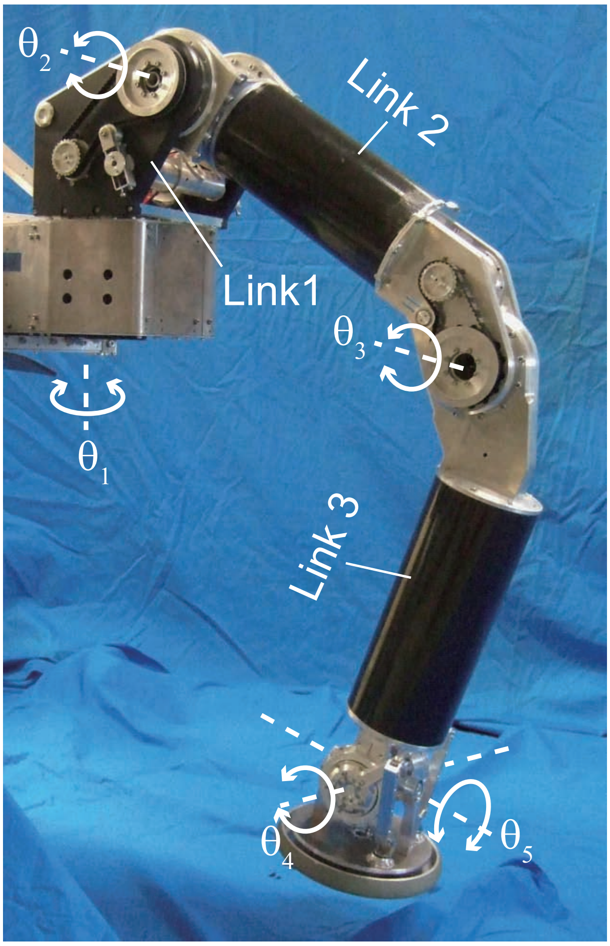


Fig.9 Prototype of the leg

reducer of each joint. The actuator output is transmitted to the Harmonic Drive by a timing belt. Each Linkage is made of CFRP and other main structures of aluminum alloy.

3.2 Ankle Mechanism

To achieve stable walking motion on rugged terrain, the ankle mechanism is needed to have functions as follows: (1)adopting the sole to undulation of terrain quickly, (2)generating counter torque against tumbling moment. It is supposed that the active ankle is suitable to satisfy both required ability simultaneously. The authors have already developed the active ankle mechanism for multi-legged walking robots and TITAN-XII is equipped with the active ankle mechanism [7]. The design concept of the active ankle mechanism is summarized below.

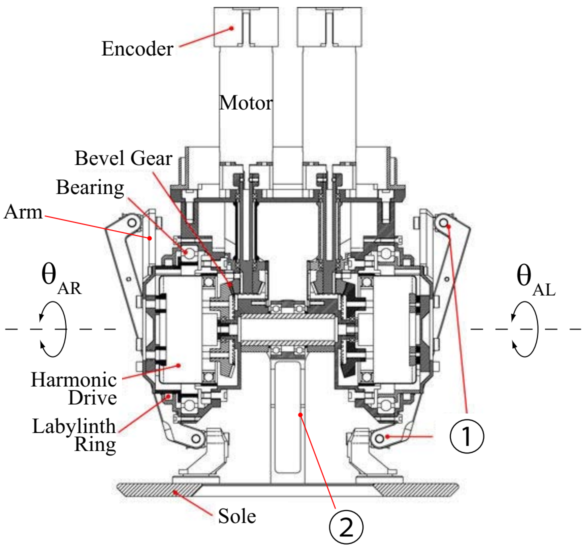
1) Lightweight: It is desirable that the inertia of the tip of the leg is as small as possible to swing the leg quickly. To make the foot lightweight, minimum number of actuators should be installed. As the posture of the sole around normal vector of the ground is not so important for the quadruped walking robot, it needs to have only 2DOF active joints.
2) Motion Range: Motion range of commercial universal joints and ball joints are not wide enough in general. Thus we designed the special universal joint with offset (① in Fig.10(a)). This universal joint permits no interference between linkage and structure, and achieve wide motion range.
3) Mechanical Strength: It should endure impact forces during walking motion. Thus this ankle mechanism is composed to structurally support impact force by the prop (② in Fig.10(a)) and actuators which support the moment acting on the foot.

Fig.10(a) shows the mechanical design and Fig.10(b) shows the workspace of the active ankle mechanism. Two 60W DC motors(Maxon RE30:310009) are installed and the actuator output is reduced by bevel gear and Harmonic Drive. This ankle mechanism is one of the differential driving mechanism. The roll angle is determined by the angle difference of the right-and-left arm, while the pitch angle is determined by the sum of both angles.

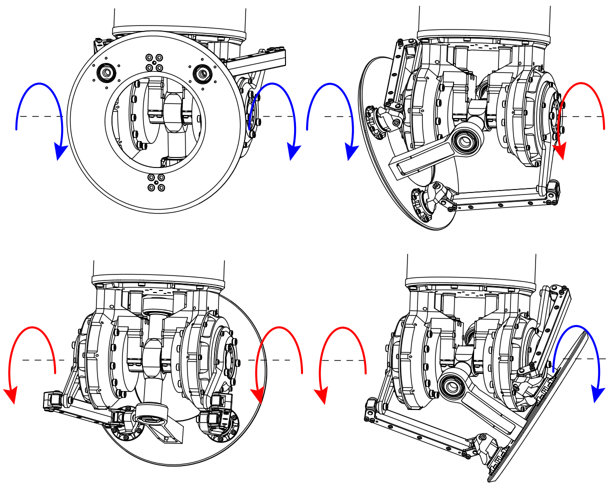
For dust-proof, the entire driving units are covered by the structure, and the labyrinth ring and the sealed bearing is used between the sliding members.

3.3 Control System

Fig.11 shows the control system of TITAN-XII. An external PC calculates the higher task such as a motion planning and the micro-controllers mounted on the robot calculates the lower task such as servo control of joints. The PC and a gateway SH2 micro-



(a) Mechanical design



(b) Workspace

Fig.10 2DOF active ankle mechanism

controller is connected via RS232C and each SH2 micro-controllers is connected via CAN-BUS. Three SH2 micro-controllers are used per one leg and thirteen SH2 micro-controllers are used in total. The control cycle of the PC is 20[msec], and that of each SH2 micro-controller is 1[msec].

Joint angles are measured by rotary encoders. Rotary encoders at joint1 to 3 are initialized by potentiometers and encoders of active ankle mechanism are initialized at initial position. Digital signals from SH2 micro-controllers are converted to analog signals by RC low pass filters and it is transmitted to each motor driver.

Table 2 Specifications of TITAN-XII

Size[m]	L:1.1×W:1.7×H:0.7
Weight[kg]	Approx.100
DOFs per 1Leg	Limb:3, Ankle:2
Motor	Joint1 to 3 294.5:1 Joint4,5 150:1
Max Leg Vertical Force	over 50[kgf](Constant)
Max Leg Horizontal Velocity	1.5[m/s] (Theoretical Value)
Joint Range	θ_1:-90 to 90[deg] θ_2:-160 to 60[deg] θ_3:0 to 180[deg] θ_4:-90 to 90[deg] θ_5:-69 to 69[deg]

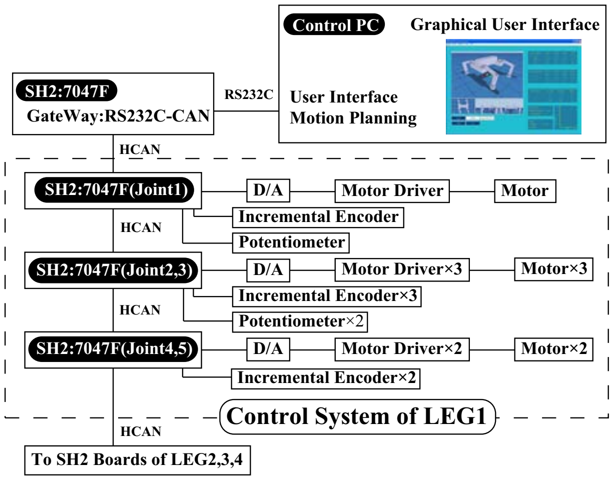


Fig.11 Control system

3.4 Experiments

Based on above considerations, we have constructed a prototype of TITAN-XII. Table.2 describes the specifications of TITAN-XII. First, we did basic experiments which are raising the body(Fig.12) and inclining the body and walking on the horizontal ground. We confirmed that TITAN-XII can perform these basic motions keeping stability.

Next, to demonstrate the basic performance of TITAN-XII, the step climbing experiment changing the body posture was conducted. The step height was set to 560mm which is difficult for TITAN-XII to climb with standard posture where the robot body is always parallel to the ground and keeps the body height constant.

Fig.13 shows the step climbing experiment of TITAN-XII. In this experiment, the total motion took 240[sec]. Through this experiment, it was qualitatively confirmed that TITAN-XII has basic capability

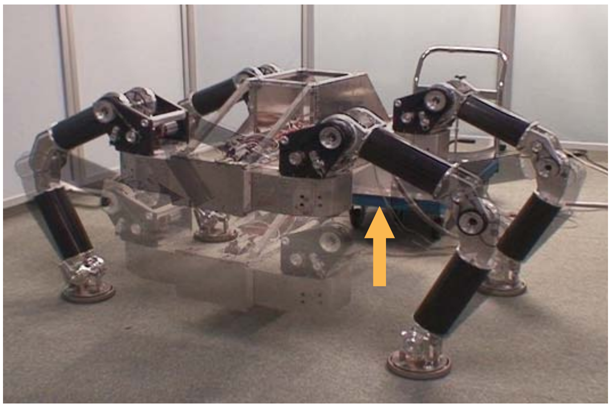


Fig.12 Body rising motion experiment

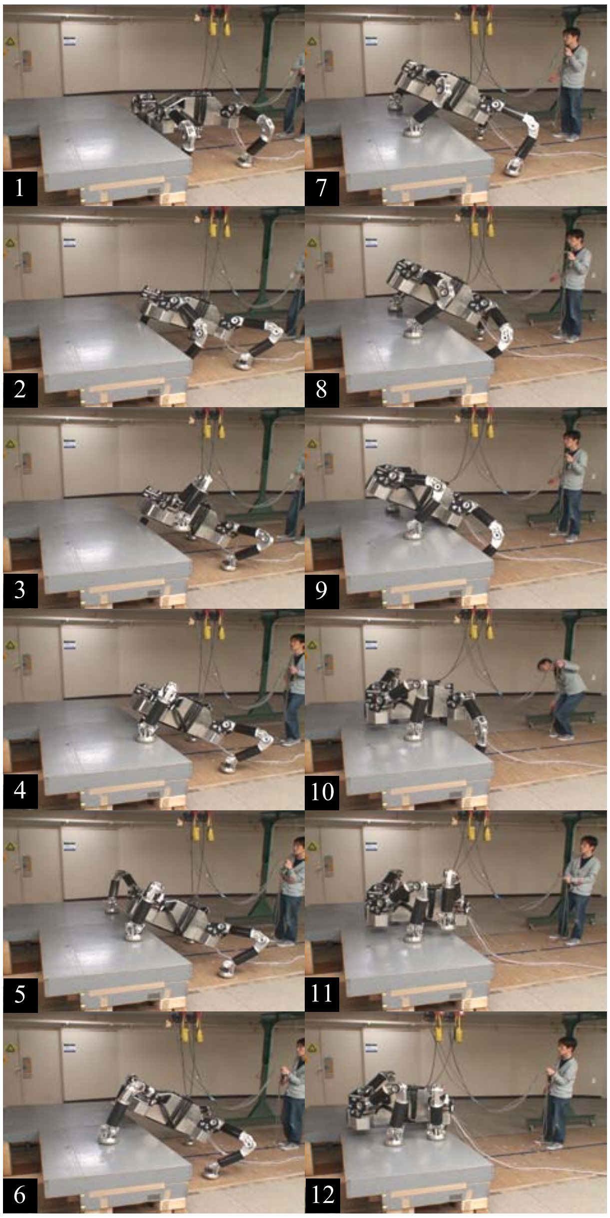


Fig.13 Large step climbing experiment

to move on rugged terrain keeping enough stability.

4. Conclusions

In this paper, background and necessity for development of a quadruped walking robot that can climb large obstacles was described. Then, optimizations of body rising motion which is basic energy consuming motion were discussed, and basic strategy to achieve energy efficient large obstacle climbing motion was derived as follows. Firstly, negative power consumption was eliminated by taking leg posture and generating internal forces appropriately, secondly, actuators were driven at high energy efficiency operating conditions by taking leg posture, generating internal forces, and setting body speed appropriately.

Furthermore, a quadruped walking robot TITAN-XII for climbing large obstacles was proposed and its mechanical design and system configuration were discussed. Finally, step climbing experiment of TITAN-XII was conducted and it was confirmed that TITAN-XII has basic ability to climb large obstacles.

We will investigate energy efficient gait control to climb large obstacles based on the strategy of optimization of body rising motion.

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