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Development of Life-sized High-Power Humanoid Robot JAXON for Real-World Use

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Abstract— **This paper presents the development of life-sized high-power humanoid robot JAXON. Humanoid robots for disaster relief assistance need the same degree of physical performance as humans. We have developed STARO as the high-power humanoid robot with a high degree of physical performance. However this is not enough for practical use of the humanoid robot in a disaster site. We consider the following as additional conditions to operate humanoid robots for disaster relief assistance outside of the lab in outdoor environments. 1) Robots have humanlike body proportion to work in infrastructure matched to human body structure. 2) Robots have energy sources such as batteries and act without tethers. 3) Robots walk with two legs or four limbs and continue to work without fatal damage in unexpected rollover. JAXON satisfied these conditions. We demonstrates the performance of JAXON through the experiment of getting out of a vehicle, stepping over walls, and operating on batteries. Further more, we assesses the performance of the strong armor and the shock absorbing structure through a backward over-turning accident.**

I. Introduction

In recent years, many researchers have studied and developed humanoid robots which can assist daily life or perform entertaining dances [1] [2] [3] [4]. On the other hand, it is expected that the humanoid robot can work and assist people not only in human living circumstances but also in disaster response situations. Such humanoid robots also have already been developed [5] [6] [7] . The hardware must satisfy the following conditions to operate humanoid robots practically for disaster relief assistance in outdoor environments.

1) Robots have humanlike body proportion to work in infrastructure matched to human body structure [1].
2) Robots have energy sources such as batteries and act without a tether.
3) Robots walk with two legs or four limbs and continue to work without fatal damage from an unexpected fall.

Humanoid robots for disaster relief assistance also have the same degree of physical performance as humans. However, such physical performance is very high in terms of speed and torque compared to previous humanoid robots. Previously, we have developed STARO [8], which accomplished the physical performance by cooling the motor driven system. In this paper, we present JAXON, which satisfies the above conditions and which are developed as a practical machine by improving on the STARO prototype. As a result, we participated in DRC (DARPA Robotics Challenge) [9] with JAXON.

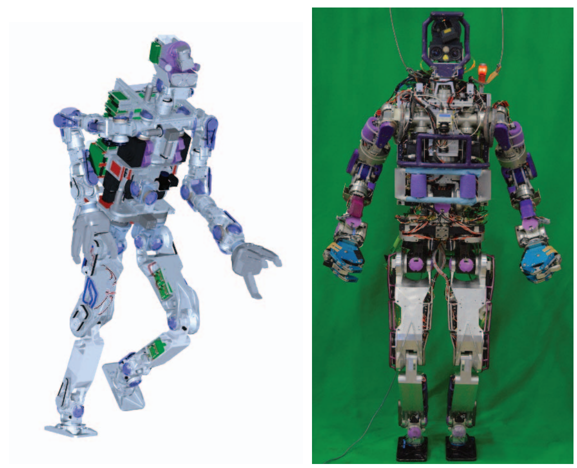

Fig. 1. Appearance of JAXON1

Fig. 2. Appearance of JAXON2

II. Specification and Feature of Life-sized High-power Humanoid JAXON

JAXON is an acronym representing:

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- J: JSK (Our laboratory's name)
- A: Anti-impact armor
- X: Extreme-power system
- O: Optimal body proportion
- N: Neon genesis humanoid

The name "JAXON" was also inspired by the fluid dancing moves of the pop-star Michael Jackson.

JAXON's principal features are humanlike body proportion and dimensions, high-speed and high-power motor driven system and wide motion range, stand-alone system by using battery, and armor and shock absorbing structure for falling.

A. Humanlike Body Proportion and Dimensions

Fig.1 and Fig.2 show the appearance of JAXON1 and JAXON2 respectively. The difference between JAXON1 and JAXON2 is not just the coloring but also circuits and design. The physical performance and structure is the same. The basic specifications are shown in Fig.3 and Table.I . JAXON is 188[cm] tall and weights 127[kg].

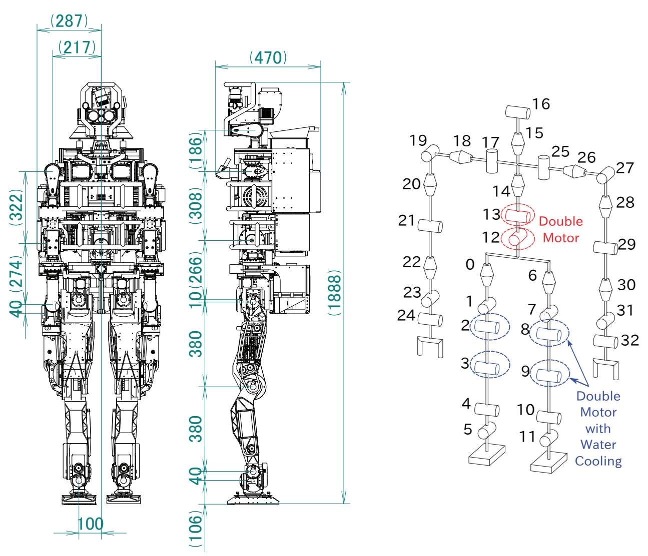


Fig. 3. JAXON's Principal Dimensions and Joint Configuration

High-power humanoid robots tend to have larger actuators and speed reducers than the other humanoids, and their dimensions are inclined to be far away from human body proportion. In fact, our STARO does not have humanlike body proportion at all. However, we attained the proportion like human body by the following three points.

Downsizing of units and components

We downsized the units of harmonic drive speed reducer and the water-cooling motor driver. The basic specifications of the speed reducer units and the motor driver are not different before and after downsizing. We downsized the speed reducer units by removing needless mechanical structures without changing the motor or the speed reducer (Fig.4). We downsized the motor driver's occupancy space by gathering receptacles in one place (Fig.5).

Effective utilization of a space

Though the control board such as motor driver are often arranged in torso link, we focused on the wider space in the thigh and shank link than other links. We placed the motor drivers of the hip pitch and the knee pitch joints in the thigh link, and placed the drivers of the ankle pitch and roll in the shank link. As a result, the motor drivers of the lower joint than hip pitch are placed in the leg links.

Alignment

The arms of STARO consist of four pairs of 2-axis modules [10] to attain simplification of design. The 2-axis module has two kinds of unit: a cantilever unit and a double-supported unit. We standardized the mechanical coupling part of each unit and this enabled us to select the mounting direction of the units (Fig.6). In this way, we attained simplification of design and humanlike arm proportion.

Because JAXON's shoulder width, leg length, and torso length are adjusted to human proportions unlike STARO, JAXON is expected to work more effectively in infrastructure matched to human body structure.

TABLE I

JAXON'S RANGE OF JOINT MOTION AND MAX TORQUE. LEFT LINK RANGE IS SYMMETRICAL TO RIGHT LINK.

Limb	Joint number	Range of joint motion [deg]	Max torque [Nm]
Head	15	-32.0 to 30.0	220[1]
	16	-32.0 to 39.0	
Torso	12	-8.0 to 8.0	574.3[2]
	13	0.0 to 32.0	
	14	-60.5 to 60.5	287.2[2]
Right arm	17	-17.6 to 81.4	220[1]
	18	-180.0 to 180.0	
	19	-180.0 to -15.8	
	20	-180.0 to 180.0	
	21	-125.5 to 60.0	
	22	-180.0 to 180.0	
	23	-89.0 to 87.0	
	24	-80.0 to 59.0	
Right leg	0	-58.8 to 62.9	220[1]
	1	-41.5 to 30.0	450[1]
	2	-121.4 to 45.0	679.9[2]
	3	0.0 to 158.9	
	4	-79.4 to 84.4	220[1]
	5	-60.0 to 60.0	

[1]ratcheting torques of harmonic drive reducer
[2]torques calculated from the current limit of motor driver system

B. High-speed and High-power Motor Driven System and Wide Motion Range

JAXON's total D.O.F. is 32 (6 D.O.F. legs, 8 D.O.F. arms, 3 D.O.F. torso, and 2 D.O.F. neck) as shown in Fig.3. JAXON has MAXON EC-4pole 30 200W motors, harmonic drive speed reducers, 6-axes force sensors in each sole and hand, posture sensors (IMU) in waist link, and Multisense SL in head link.

TABLE II
COMPARISON AMONG ACTUATOR SPECIFICATION, SPEED REDUCER SPECIFICATION AND NECESSARY TORQUES FOR STEPPING OVER THE WALL

Joint name	Torques necessary for stepping over the wall[Nm]	Max torques by current limit[Nm]	Harmonic drive type	Ratcheting torques[Nm]
Crotch roll	159.9	393.6	CSD25-160	450
Crotch pitch	429.3	492	CSD32-100	1000
Knee pitch	418.0	492	CSD32-100	1000
Ankle pitch	96.6	295.2	CSD20-160	220
Ankle roll	49.5	247.5	CSD20-160	220

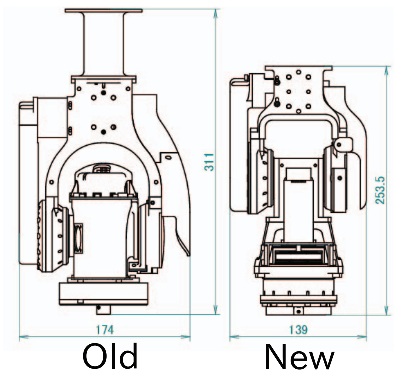
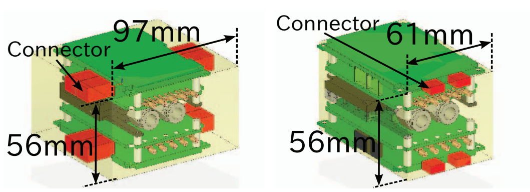


Fig. 4. Comparison between new and old joint unit



(1) Old (2) New

Fig. 5. Comparison between new and old motor drivers

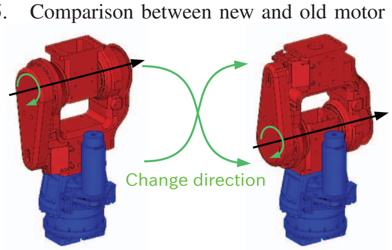


Fig. 6. Unit Mountable in Dual Direction

All of JAXON's joints use a high-speed and high-torque actuation system [11]. The hip pitch and knee pitch joints are constructed with water-cooling double motor units [8], and the torso roll and pitch joints with natural air-cooling double motor units (Fig.3). High-speed and high-torque actuation system exhibited the performance of a motor without burnout by keeping the estimated motor core temperature below the limit temperature [11]. Urata et al. further reported that a water-cooled motor could accept about four times larger current than a natural air-cooled motor [12]. In addition, after STARO supported 100[kg] (body weight 50[kg], weight load 50[kg]) for about 1400[sec] with a posture bending knee at 98[°], which is equipped with water-cooling double motors in knee joints, the motor core temperature did not reached 100[°C] [8].

We determined the link length, the actuators and the speed reducers in leg links as below.

1) Decide the length of leg links from the seat height of the car
2) Calculate the torques necessary for stepping over the wall in height of 400[mm] in simulation
3) Select the actuators and speed reducers by the torques

We determined the thigh and shank length to 380[mm] so that JAXON's foot can reach the ground as it is sitting on the car's seat. Table.II shows the torques necessary for stepping over the wall in simulation. The second column shows the max torques calculated from the current limit of motor driver, the torque constant, and the gear ratio. We decided to use a water-cooling double motor unit in crotch pitch and knee pitch joints, and a natural air cooling single motor unit in other joints. The right edge column shows ratcheting torques of harmonic drive reducers. We selected CSD32-100 in crotch pitch and knee pitch joints, CSD25-160 in crotch-roll, and CSD20-160 in other joints.

Especially, JAXON's legs are high-power but designed in smart shape. Since JAXON can cross their legs as shown in Fig.7, it is expected to contribute to the balance control.

Because STARO could not stand up from a prone position due to the torque limits of waist joints, JAXON has CSD32-160 in waist three joints and uses natural air cooling double motors in waist roll and pitch joints.

C. Stand-alone System by Using Battery

Unlike STARO, JAXON has batteries and a wireless router for operating with no tether. Table.III shows the specifications of LiFe batteries equipped with JAXON. JAXON loads three 72V batteries for driving motors, three 12V batteries for driving control boards, and two 12V batteries for driving PC, cooling-pumps and other devices. We decided the loading number and the distribution of each battery so that JAXON can work general tasks for one hour and battery charge of each system reduce equally.

D. Armor and Shock Absorbing Structure for Falling

Humanoid robots can fall over easily because they move as keep their balance with their legs. Though many researchers have studied about over-turning avoidance [13] [14] [15]

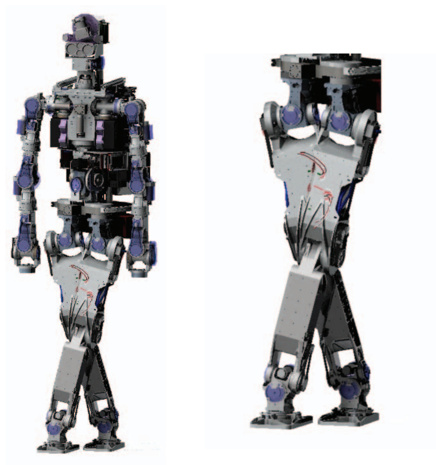


Fig. 7. JAXON's crossing leg posture

TABLE III
SPECIFICATION OF BATTERIES

Name	1 cell voltage[V]	1 cell capacity[Ah]	Parallel number	Series number	Voltage [V]	Capacity [Ah]
12V battery	3.3	15	1	4	13.2	15
72V battery	3.3	2.5	1	22	72.6	2.5

[16], humanoid robots may fall down in some cases. Aiming to prevent fatal damage in unexpected falling, we equipped JAXON with strong armor and a shock absorbing structure.

First, we explain strong armor. Since the lower body receives smaller impacts than the upper body in an over-turning, we protected leg links by strong armors. We stored the major part of motors, harmonic drive reducers, and motor drivers inside of the strong thigh and shank links, which are formed by cutting one chunk of metal. We protected by stainless and titanium covers (shown in Fig.8) the other exposed parts such as pulleys and belts for the purpose of designing, assembling, and maintenance.

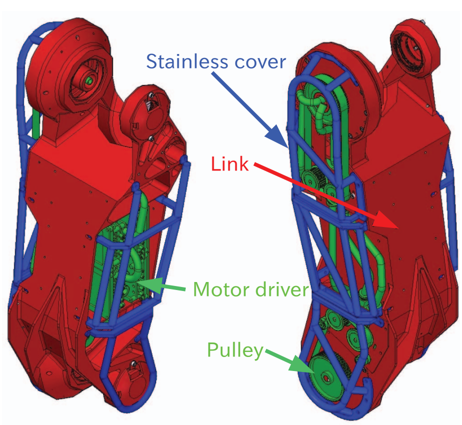
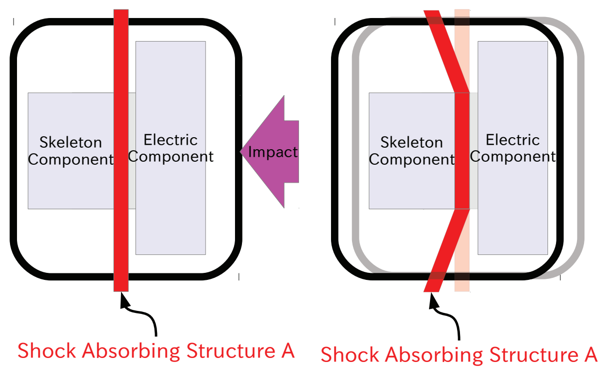


Fig. 8. Strong Armor in Thigh Link

Next, we explain the shock absorbing structure of upper body. The upper body receives larger impacts than the lower body in an over-turning. Kobayashi et al. [17] proposed the structure to reduce the impact by using active shock absorbing exterior. However, it is difficult to equip JAXON with active shock absorbing armors for the problem of weight, power source, and space, and we resigned it. On the other hand, we can reduce the impact of over-turnings by using non-active soft armor [18]. However, as for heavy robots, enough soft armors to absorb the impact deteriorate thermal radiation performance and manipulation function.

Then we adopted shock absorbing structures for vehicle. Vehicle cabins are stronger and stiffer than the shock absorbing structures, allowing the shock absorbing structures to deform and dissipate energy in the case of an impact. As shown in Fig.9, skeleton components and electrical components consist of strong structures, and the other parts are easy to deform and absorb the impact of over-turnings. This protects important parts such as skeleton components and electric components from fatal damage. In all reason, shock absorbing structures can not endure the several over-turnings unlike active shock absorbing armors or soft armors. Therefore, we designed shock absorbing structures to endure the two over-turnings. We decided the strength of the shock absorbing structures through preliminary experiments. We gave the structure a drop impact corresponding to a over-turning twice, and we adjust the strength of the structure so that the maximum deformation should be lower than the defined value.



(1) Before impact (2) After impact

Fig. 9. Shock Absorbing Structure of Upper Body

III. Experiment to Evaluate JAXON's Performance

We conducted the experiments of getting out of car, stepping over wall, and operating on battery, and the performance evaluation of the shock absorbing structures.

A. Experiment of Getting out of Vehicle

Utilizing JAXON's long legs, we conducted the experiment of getting out of the vehicle with no jig, whose seat height is 770[mm]. In this paper, we generated the motion of getting out of a vehicle by interpolating the given intermediate postures with the robot's dynamic balance controller. Fig.10 shows the JAXON's motion of getting out of the vehicle.

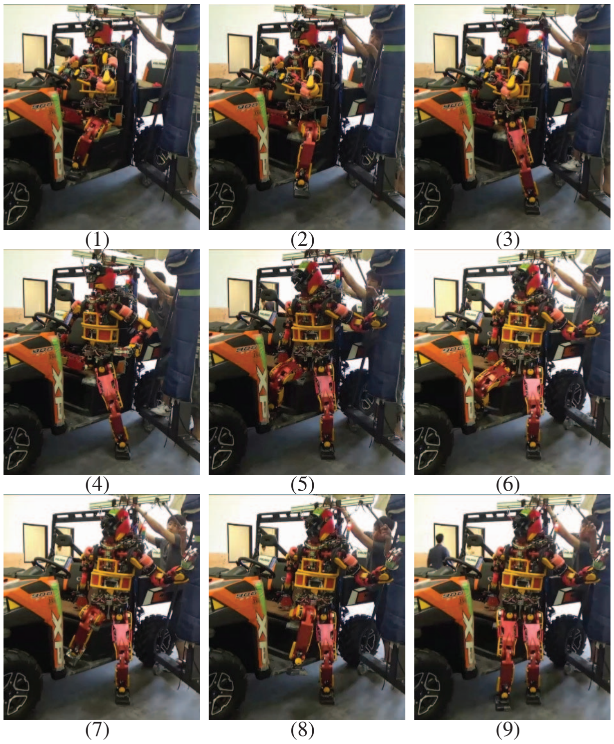


Fig. 10. Experiment of Getting out of Vehicle by JAXON

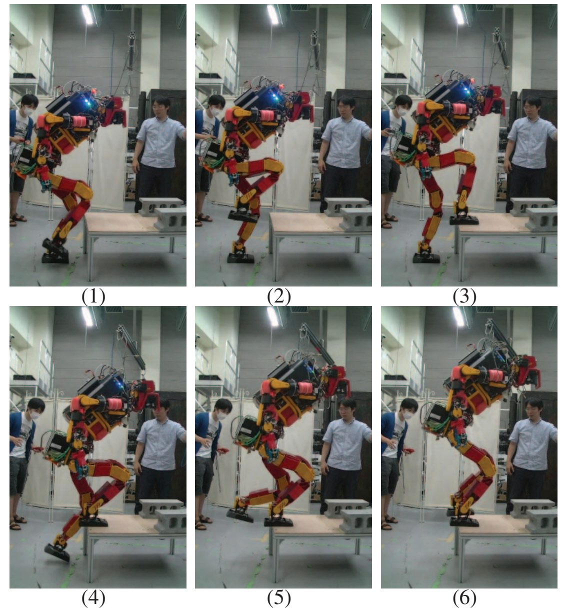


Fig. 11. Experiment of Stepping over Wall by JAXON: Wall is 400[mm] high.

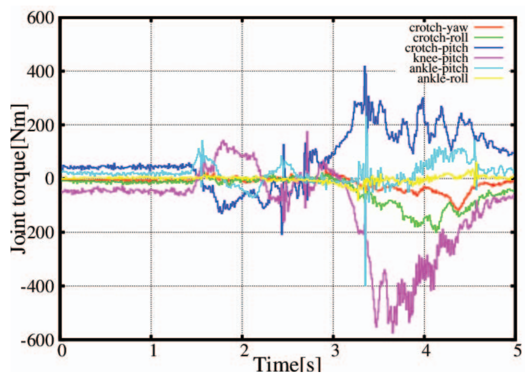


Fig. 12. Torques Estimated from Motor Current during Stepping over Wall(0-1.7sec: double support phase,1.7-2.7sec: left support phase,2.7-3.4sec: double support phase,3.4-4.5sec: right support phase,4.5-sec double support phase)

B. Experiment of Stepping over Wall

We confirmed the maximum height of wall which JAXON can step to show the utility of JAXON's high-speed and high-torque motor driven system. In this paper, we generate the COG trajectory keeping the robot's dynamic balance stable from the trajectories of foot position, posture, ZMP, and COG height. Then we calculate the whole body motion trajectory by using of COG Jacobian. The JAXON's motion of stepping over a wall is shown in Fig.11. JAXON was able to step over the wall 400[mm] in height by using only legs, though STARO was able to step over the wall by using legs and arms [8]. Fig.12 shows the torques calculated from the current of the raising leg joints. This graph informs us that knee joints need at most about 600[Nm] torques.

C. Battery Operated Experiment

We measured maximum active time through the experiment of operating only on batteries. Fig.13 shows the transition of battery's voltage. Jaxon was able to conduct the moving tasks such as walking terrain and stepping up stairs and the manipulation tasks such as drilling and valve rotating motions for about 70 minutes with no tether.

D. Performance Assessment of Shock Absorbing Structure

We assessed the performance of the shock absorbing structure by observing the deformation of it when JAXON fell down. JAXON's motion of falling down backward is shown in Fig.14. We guess that a communication error occurred in the motor driver of an ankle joint, the motor driver powered off, and JAXON has fallen down with the other motor drivers powered on. Fig.15 shows the deformation of the shock absorbing structure by the backward overturning. The backpack is displaced forward because the backpack received the large external force from the back and shock absorbing structure deformed. However, the important parts such as joint drive components, skeleton components, and electric components are not damaged. Then JAXON accomplished stepping up the stairs after rebooting its system without repairing its hardware. This suggests us that the shock absorbing structure take enough effect.

IV. Conclusion

In this research, we developed JAXON as a humanoid robot which can work practically in support activities on disaster sites. JAXON's features are that it has humanlike body proportion to work infrastructure matched to human body structure, that it have batteries as energy sources and act without tethers, and that it continue to work without fatal damage in unexpected falling thanks to strong armors and

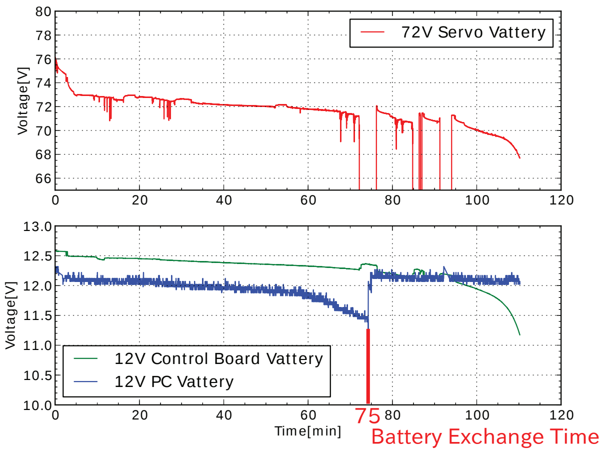


Fig. 13. Transition of Battery Voltage: The sudden changes of voltage is due to switching emergency stop.

a shock absorbing structure. Suggesting the utility of these features, we conducted the experiments of getting out of a vehicle, stepping over a wall, and operating on battery, and assessed the performance of the shock absorbing structures.

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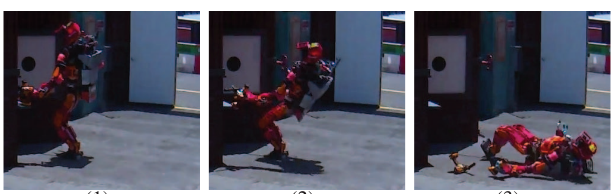

(1) (2) (3)

Fig. 14. JAXON’s Backward Over-turning

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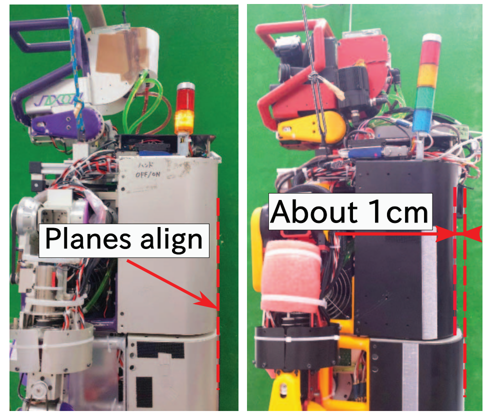

(1) Before Deformation (2) After Deformation

Fig. 15. Deformation of Shock Absorbing Structure by backward over-turning (side view)

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