Camera Arm System for Disaster Response Robots
(1st Report: Design Strategy and Evaluation of Prototype Development)

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Abstract
In this paper, design and development strategies of camera arm systems for disaster response robots are fully discussed. Unlike the previously-provided system, which has been used repeatedly for information gathering purpose at the FUKUSHIMA nuclear disaster in 2011, a camera arm is mounted on a crawler-type remote operation robot. A wide variety of design aspects for practical uses of camera arm systems, including functional requirements, space-effective realizations and experimental evaluations, are discussed.
Keywords: disaster response robot, rescue engineering, manipulator, camera arm, mechanical design

1 Introduction
This paper presents design and development strategy of camera arm systems for disaster response robots. The Great East-Japan Earthquake in 2011 has caused the serious nuclear disaster at FUKUSHIMA in Japan. Our information-gathering remote operation robot, Quince specialized for this disaster [1], has been used repeatedly at the disaster site to investigate the high-radiation inside of the collapsed reactor buildings including the top floor, leading to the significant reduction of on-site worker's radiation exposure [2], [3].

Under NEDO Research and Development Project for an Unmanned Disaster Response System (FY2011-FY2012), in order to enhance the robot information gathering ability, a remotely operated robot system, named Sakura II, has been developed as in **Fig. 1** [4].

In addition to fundamental improvements of payload-carrying capacity and dust/water proof capability, a camera arm system is newly developed and mounted. Unlike the previously-provided system, where the camera unit is rigidly fixed without arms, the versatility of movable camera position and orientation together with the ability of light-work gripper operations are offered. Here, the camera arm system is focused, and its target performances, space-effective machine designs and performance evaluations are fully discussed.

In terms of mobile manipulators, tremendous efforts can be found in the literature, *e.g.* [5], [6], in which primary issues are on kinematical or dynamical studies rather than hardware realizations. Among those, design topics are briefly presented in Helios [7], but cameras are not mounted meaning that remote operations are out of its scope. As also stated in [8], for unmanned investigation missions, camera maneuvering functions both for remote controls and investigations are quite important and machine designs should be considered along this line for practical uses. In [9], although the remote operability is included in its target specifications, cameras cannot be seen in the presented drawings and pictures, and besides, water/dust proof abilities are not pursued. PackBot [10] is one of the successful robots usable in difficult environments. Unfortunately, any of its internal structures are not known typical to military-use products (note that its configuration of crawlers as well as flipper arms are quite different from Sakura II in **Fig. 1**, and in fact, PackBot could not climb to the upper floor at the reactor building right after the nuclear disaster [10]). In KOHGA [11], the importance of camera systems is discussed, but double-head

Fig. 1 Camera Arm System on Disaster Response Robot (Sakura II)

Table 1 Basic Specification of Camera Arm System

Mounting	on disaster response robots
Equipment	wide/high resolution camera, lights, gripper
Functions	posture holding without power consumption collision protections dust/water proof (corresponding to IP67) absolute joint angle sensing (all joints)
Link Structure	0.6m x 3 links (changeable) 8 joints (in total)
Camera	2.3m (maximum height from the floor)
Work	4.5kg (depending on link extensions)
Camera Joint	pan/tilt axes (continuous rotation available at pan axis)
Gripper Joint	grasping/wrist rotating axes (continuous rotation available at wrist axis)
Weight	16kg: arms, 4kg: base and connecting plates
Connection	power: 30V, communications: CAN, Ethernet

snake-like robot, focusing on near-floor investigations, cannot investigate high locations.

2 Performance Requirements

For camera arm systems, 1) without deteriorating the traversing ability of crawler robots, it is required to be capable of 2) investigating environments through clear images by movable camera unit including overhead locations or narrow tight spaces and 3) performing light-work tasks such as sampling, debris removing and door opening. Furthermore, various functional requirements involved by operating environments, times, and others related to remote operation aspects must be considered. The basic specification is listed in **Table 1**, and the target performance specified in this project is summarized below:

(1) Traversing Ability of Disaster Response Robots
- Not deteriorating the traversing ability. Typically traversing on unknown irregular fields including 45-degree stair climbing is required.
- Folding entire camera arm systems, so that it can be included inside the crawler robot footprint with allowable gravity center location to avoid destabilization in traversing on irregular terrains or climbing stairs as well as to perform point-turn motion at narrow space.

(2) Enhancement of Information-Gathering Ability
- Equipping with a movable high-resolution camera and a lighting unit for dark-space investigations.
- Enabling versatile positions and orientations of camera unit for high-position and narrow-space surveys such as ducting pipes arranged at ceiling.

(3) Light-work Operation Ability
- Equipping with a gripper to operate remotely light-work tasks such as sampling, debris removing and door opening.

(4) Power Consumption
- Holding the pose of camera arm without wasting battery power (in remotely-operated investigation, considerable long time is expected to be of staying at rest as compared with the time of moving).
- Switching remotely lights, motor drivers and other circuit boards to reduce power consumption according to the necessity.

(5) Collision Protection
- Offering collision protection functions for stress-free and successful operations in unknown narrow tight spaces or easily balance-losing fields.

(6) Dust/Water Proof
- Allowing unrestricted operations even in dusty or water-sprinkled fields typical of disaster sites.
- Prohibiting, in particular, any exposures of electrical components to the outside atmosphere.

(7) Others for Alleviation of Operator Stress [8]
- Maximizing joint angle ranges, or providing continuous rotations if applicable.
- Sensing absolute angles for all joints.
- Switching remotely local controller function as active or passive for preferred joints.

3 Preliminary Design

Before addressing detailed design issues, the design strategy to meet the requirements above is briefly discussed here. With the overall view shown in **Fig. 2**, the component specification of each joint in the camera arm is listed in **Table 2**.

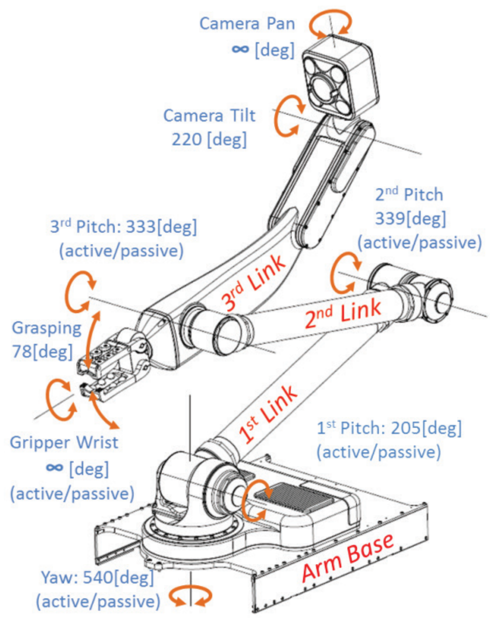

Fig. 2 Overall Structure and Joint Assignment

Table 2 Specification of Joint Components

Joint Axis	Torque	Gear Ratio	Posture Holding	Collision Protection
Yaw Axis at base	30mNm/A	405	Electromagnetic Motor Brake	Friction Coupling
Pitch Axis at Base	60mNm/A	480	Electromagnetic Motor Brake	Friction Coupling
Pitch Axis at Elbow	38mNm/A	480	Electromagnetic Motor Brake	Friction Coupling
Pitch Axis at Gripper	30mNm/A	540	Electromagnetic Motor Brake	Friction Coupling
Rotating Axis at Gripper	30mNm/A	162	Electromagnetic Motor Brake	None
Grasping Axis at Gripper	15mNm/A	870	Worm Gear	Friction Clamping
Tilt Axis at Camera	15mNm/A	270	Worm Gear	Friction Belt
Pan Axis at Camera	15mNm/A	270	Worm Gear	Friction Belt

3.1 Design Strategies for Functionality Realizations

Overall Link Structure and Joint Assignment: To allow wide-ranging camera positions and orientations, it is strongly desired to configure the arm structure as long as possible with appropriate joint assignments. For this purpose, it is structured by three link frames with the camera/light unit at its head, and each link length is maximized but possible to be included by folding inside the crawler robot footprint (0.6m each), so that the camera image can reach to overhead positions as well as the robot can make a point-turn at narrow space.

Besides, at the end of the 2nd link, two-joint gripper will be installed for light-work operations. The shape of the 3rd (most outer) link is bended slightly to the above to locate the camera on an applicable position for remotely operating gripper tasks as well as crawler robot movements. These three elevation link structure is formed on a yaw joint at the arm base. Each joint angle range is maximized with absolute angle sensing. In particular, the base yaw axis will be able to rotate in [-270 +270] degree with mechanical limiters.

Three link frames will be composed by light and tough carbon pipes connected through duralumin-made joint units, where the 1st and 2nd pipes can be easily changed to a different length (shorter) link if necessary.

Arm Posture Holding: To prolong the limited energy source, non-backdrivable gear configurations or electromagnetic motor brake will be adopted, so that the arm posture can be kept without consuming any additional electric power. Associated also with the remote switching feature of active/passive joint controls, the selection of posture-holding means for each joint, either brake or worm gear, is indicated in **Table 2**.

With this design policy, thermal time restriction of motors and motor-drive circuits can be significantly facilitated in the component design process. Mainly, torque constant of motors and maximum current of motor drivers will be focused.

Active/Passive Switching of Joint Controls: For all the backdrivable joints, remote switching features of active/passive control should be allowed to promote the operability of the arm system. This can be provided through local joint controller functions. The discussions of controller architecture can be found in [12].

Friction Coupling for Collision Protections: In order to avoid the destruction due to collisions as much as possible, frictional dissipations of impulsive-force energy will be implemented at several parts through simple clamps, friction belts and built-in joint torque limiters, where intentional slipping will occur for pre-assumed excessive external forces.

Dust/Water Proof and System Independence: In order to promote dust/water proof property and to reduce the dependence to other robot systems, all the necessary electrical components, such as power supply circuits, motor controllers or wireless connection units, must be arranged inside the arm body while only power supply and communication cables (CAN, Ethernet) are allowed via water proof connection to the crawler robot.

3.2 Camera/Light Unit

Camera Model: For visual-based investigations, the quality of camera image is the most important element. The camera unit selected here is the exactly same model as the one used at the actual nuclear disaster missions (Axis Communications AB) [1], [2]. Although it is heavy to be attached at the arm tip, the resolution and the clearness have been found to be appropriate through the actual missions [3].

Joint Assignment: Two orthogonal joints of pan/tilt axes for maneuvering the camera direction should be provided with functions of their absolute joint angle sensing. In particular, for look-around 360-degree views to be easily available, continuous rotation of the pan joint is strongly demanded, so that it can be operated without the care of the joint angle range. As detailed later, functions of collision protection and posture holding by no-motor-current are necessary as well.

Impulsive-Force Resistance and Heat Dissipation: The camera/light unit, located at the arm tip, is most likely to have collisions to surroundings. Moreover, due to the necessity of high illumination, this will be the most heated part in the arm structure (rather than motor circuits). Thus, 1) dust/water proof, 2) shock resistance ability (besides collision protection mechanisms at the joints) and 3) effective heat dissipation must be in consideration. To meet these requirements, a design approach of packing all the necessary electrical components by metal materials is adopted, providing suitable features for waterproof sealing, impulsive-force resistance and thermal conduction.

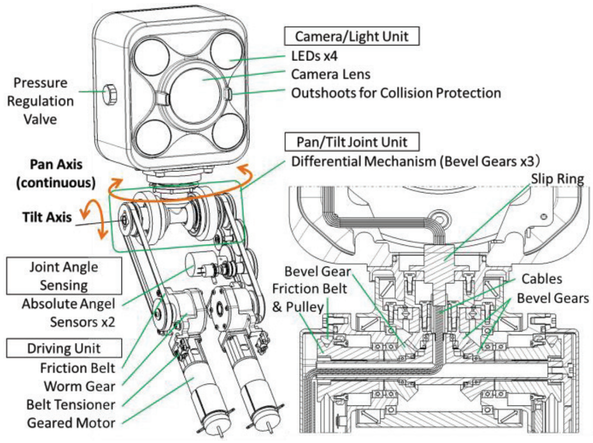

Fig. 3 Joint Structure of Camera/Light Unit

3.3 Gripper Unit

Joint Assignment: As for the applicability to various uses by minimum requirements, two axes of gripping and endless wrist rotating are considered with absolute angle sensing for both joints. Avoiding optimization issue for the gripper shape, it will be designed to allow easy-change of fingers according to target object shapes.

Collision Protection: Note that the gripper is another likely part of collisions with external objects. To protect its gear train from possible impulse and for stress-free operations, an adjustable friction clamping is applied for fixing the finger.

4 Design Details

The design details of the camera/light and the gripper units with their joint configurations are fully discussed here. Note that for the pitch joint configuration, the design issue is more involved, and only the summary is given in this paper. Its details with evaluation experiments are discussed in [12].

4.1 Joint Mechanism Design of Camera/Light Unit

Ensuring the consistency of the space-effective arrangement and the functionality realization has been a primary issue of this joint design, *i.e.*, two orthogonal joints of pan/tilt axes must be configured 1) compactly at the narrow bar-like space of the arm tip with the functions of 2) the collision protection, 3) the posture holding without consuming motor currents, 4) the absolute angle sensing, and 5) the dust/water proof.

Space-Effective Design of Joint Mechanism with Collision Protection and Posture Holding Functions: In this project, a differential mechanism by three bevel gears is applied for the compact configuration of two orthogonal joints as shown in **Fig. 3**. Then, pairs of

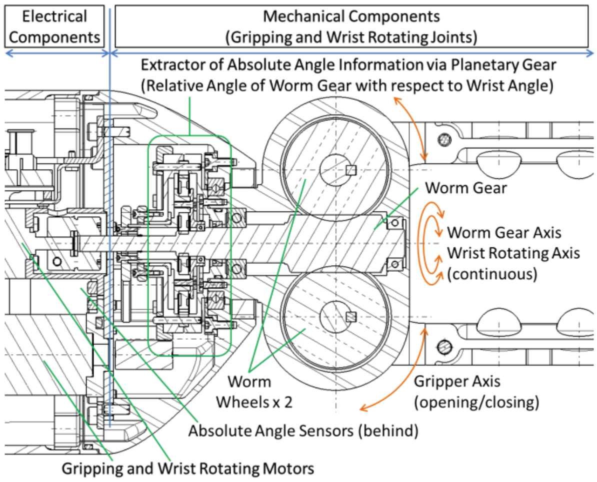

Fig. 4 Internal Structure of Gripper Joint

friction belts and worm gears are space-effectively arranged for driving-force transfers, collision protections as well as no-motor-current posture holdings. Besides, adjustment mechanisms of belt tensions are installed to ensure successful slipping between the differential mechanism and the worm gear whenever pre-assumed excessive force occurs.

Absolute Angle Sensing: Even in the case of the slipping, the absolute angles of the pan/tilt joints can be effectively measured by mounting sensors connected appropriately to the differential mechanism. It should be also noted that a slip-ring is internally installed at the pan axis, allowing its stress-free continuous rotations.

Light Unit Design for Thermal Dissipation: The heat reducing and releasing must be taken into full account as mentioned before. Here, the lighting, or heating, source is divided into four LED lights, and current supplied for each LED circuit is regulated by a current controller. While the total brightness is sufficiently achieved by four LEDs, the produced heat can be physically distributed suitable for its dissipation through the metal housing. Note that a pressure regulation valve is also prepared on it to avoid the sealing deterioration due to dramatic change of the internal pressure through water spray cooling.

4.2 Joint Mechanism Design of Gripper Unit

A primary difficulty for the gripper joint design is caused by the fact that while the wrist joint is preferred to be able to rotate endlessly, the griping joint must be placed beyond this continuously rotating joint, and both of absolute angles should be measured. The devised mechanism in this project is shown in **Fig. 4**.

Joint Mechanism and Collision Protection: In this design, a worm gear is used for compact drive of both fingers, and its drive shaft (worm gear shaft) is arranged in the identical line with the hollow wrist rotating shaft. The interference between two joint axes can be removed by local position controllers if each absolute angle can be obtained independently.

Absolute Angle Sensing: The absolute angle information for the gripper opening/closing, in fact, corresponds to the relative angle of the worm gear shaft with respect to the wrist-rotating shaft. To extract this relative angle, the differential property of planetary gear system is tactfully used, where the sun gear is embedded on the worm gear shaft and the outer gear is rigidly fixed on the wrist rotating shaft, associating the career angle relative to the link frame with the absolute angle information of the gripper opening/closing. Note that the absolute angle of the wrist rotation can be easily gained by an absolute sensor mounted on the link frame by a usual manner.

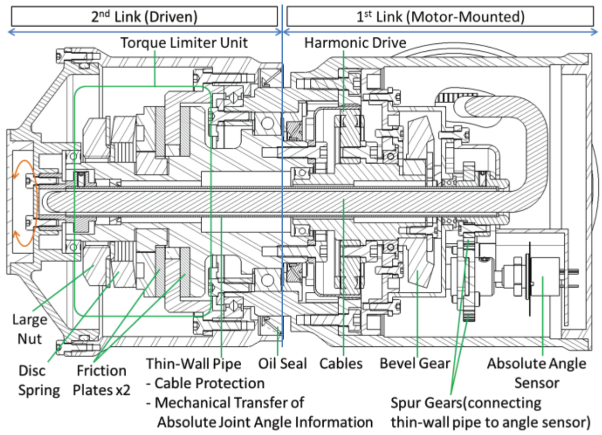

Fig. 5 Internal Structure of Elbow Pitch Joint

Advantages: In this design way, several advantages can be taken such that 1) the endless wrist rotation is available, 2) the absolute angle information of each joint is independently obtained, and 3) all the electrical elements, which require the connecting cables for power supplies and information transfers, can be arranged in the space not beyond the moving part, suitable to sealing design for dust/water proof.

4.3 Pitch Joint Mechanism

For pitch joints having the role of elevations of the camera and the gripper, there are several required functions of 1) transferring relatively large torques, 2) passing electrical cables through joints, 3) holding the arm posture without motor current consumptions, 4) protecting gears and other mechanics from impulsive forces applied by collisions, and 5) sensing absolute joint angles. In this paper, only the cross section of the elbow joint is depicted in **Fig. 5**. The evaluation results for this joint structure are detailed in [12].

5 Performance Evaluations

5.1 Dust/Water Proof Capability

The water proof ability has been evaluated by actually immersing the arm into 0.5 m depth of water at 17 degree of temperature as shown in **Fig. 6** (top), where all the joints have been kept moving externally during a half hour of the testing. Before this evaluation, a number of wet detecting stickers were put on the internal walls. It was then confirmed that all the faces of both moving and not-moving, were effectively sealed against the water pressure.

5.2 Heat Dissipations

The effectiveness of the sealing, in general, can be a detrimental factor regarding thermal dissipation. The amount of heat produced by electric circuits must be balanced with heat dissipation ability under the

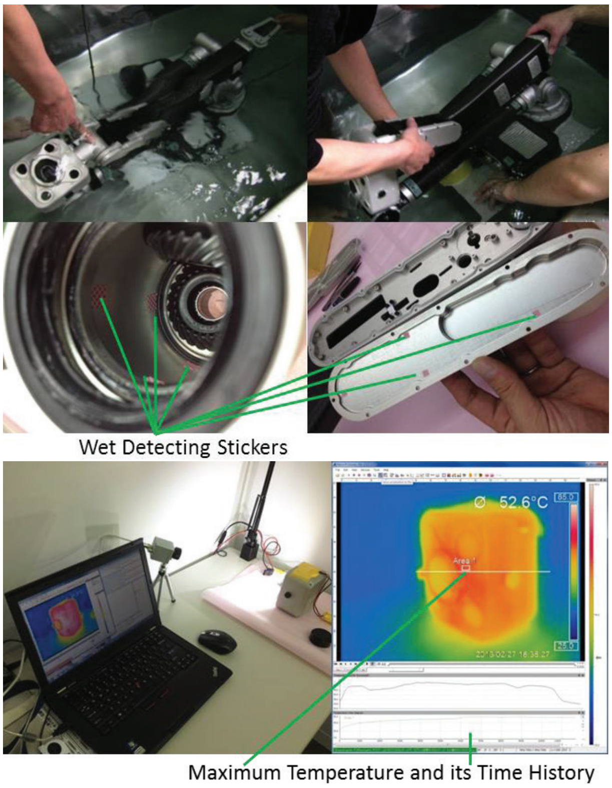

Fig. 6 Water Proof Testing (top) and Thermal Dissipation Evaluation (bottom)

allowable temperature.

The mechanical configuration adopted here does not require continuous motor currents for posture holding. A few heat sink plates adhered on the CFRP frame, also shown in **Figs. 6** and **7**, have been proved to be enough for the thermal saturation.

As discussed before, the light unit is the most heat-generating portion in the developed system. The result of thermal rating is shown in **Fig. 6** (bottom), where the surface temperature has been measured for 3 hours. Under the condition of 25 degree room temperature with no winds, the most heated portion was saturated around 53 degree, while sufficient brightness is obtained and the camera inside the heated housing has been confirmed to operate correctly as seen in **Fig. 7**. The successful functioning of the heat-source decentralization, the LED current regulation and the heat dissipation design has been verified.

5.3 Power Consumption and Joint Control

The reduction of power consumptions is essential not only for disaster response robots, but also for any moving robots, which have to inevitably equip their own body with energy source. **Figure 7** shows a typical remote operation example of collecting samples, where pictures of the camera view and the electrical power supply are imposed. Note that the external power supply is used here only for presentation purpose, and 30V similar to the battery voltage mounted in the crawler robot (28.8V nominal, 24Ah capacity) is supplied.

For the developed camera arm, the necessary operation current at the stationary state of the arm has been 1.3A, and 1.9A has been required if the light unit is turned on. In the time that two pitch joints are driven simultaneously in the sampling operation, the current supply in total has been around 3A under 30V supply.

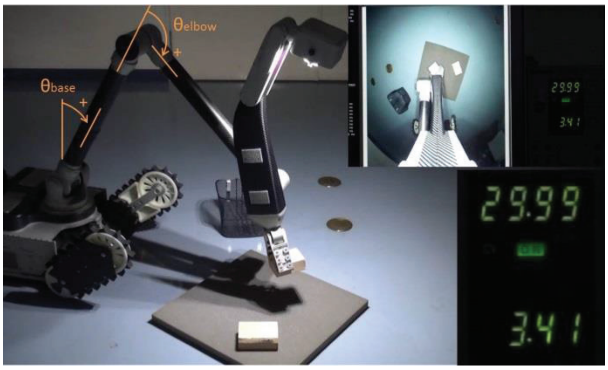

Fig. 7 Sampling Operation and Power Consumption

Figure 8 shows a time history of the motor currents, the brake states, and the joint angles for this sampling motion, where two pitch joints of the base and the elbow are taken as representatives. In the time that the joint is not driven, it is fixed by the motor brake. Whenever the joint drive is occurred, the sequence of 1) holding the joint angle by the local servo controller, 2) releasing the motor brake, 3) driving the motor, has been processed. These drive sequence is automatically proceeded at the start or the end of the joint drives except for several worm-gear joints. The entire posture of the camera arm can be kept immediately whenever the operator loses hold of the gamepad controller.

5.4 Hill-Climbing Ability: Stair Traversing

As a typical example, the stair-climbing robot with the developed camera arm of around 20kg on its body is shown in **Fig. 9** (left). By folding the arm compactly, the robot can go up without the losing of the gravity balance, and can make a point-turn motion at the stair case landing. Note that the crawler robot can be also remotely operated by this camera position. The highest location of the camera can reach beyond 2m from the floor. The visual investigation of high positions, such as ducting pipes arranged at the ceiling, can be performed by the robot at resting state.

5.5 Remote Operability Test: Door Opening

In order to evaluate the remote operability by an operator far apart from the robot, debris removing and door opening have been repeatedly performed as indicated in **Fig. 9** (middle, right). Both operations can be completed by a couple of trials (detailed in [12]), showing the validity of the design approach including the camera position. At the vicinity of the gripper, however, the following matters have been observed, 1) defection of a sense of depth, and 2) deterioration of the visibility due to the lighting reflection.

The long-distance object can be adequately and clearly seen through the camera/light unit image. For an object close to the gripper, however, it is hard to sense the depth information. For the dark-space operation, moreover, depending on texture of the object surface, the tip of the gripper cannot be seen through the camera image due to the light reflection. As improvements, the addition of secondary camera, where different direction images can be available, and the adjusting function of the brightness, are considered.

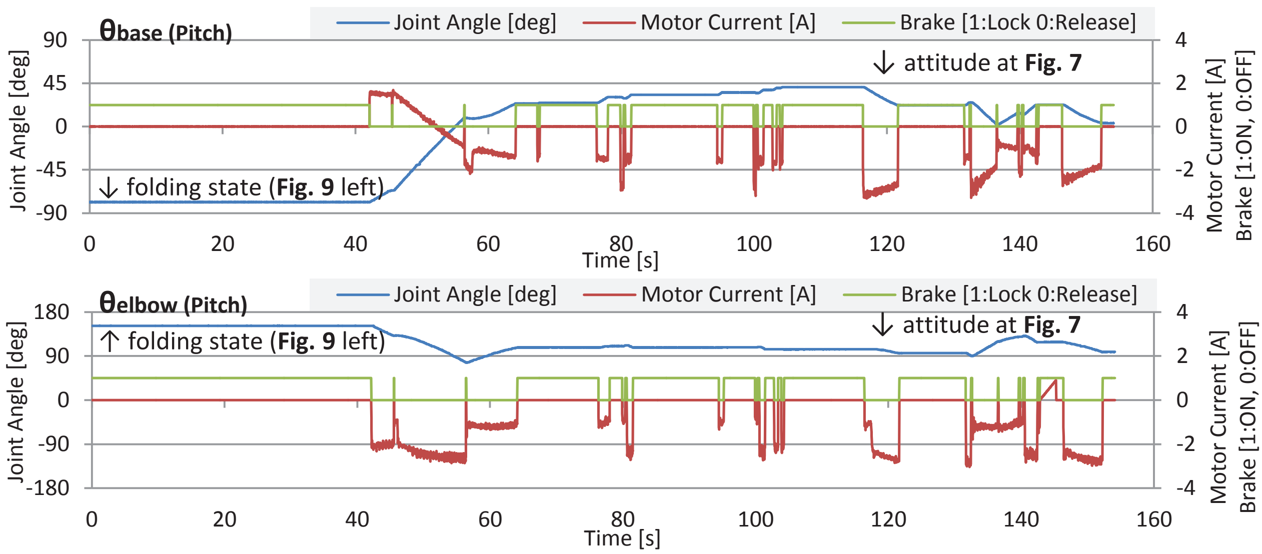

Fig. 8 Joint Angles, Motor Currents and Brake States of Base and Elbow Pitch Joints in Sampling Operation

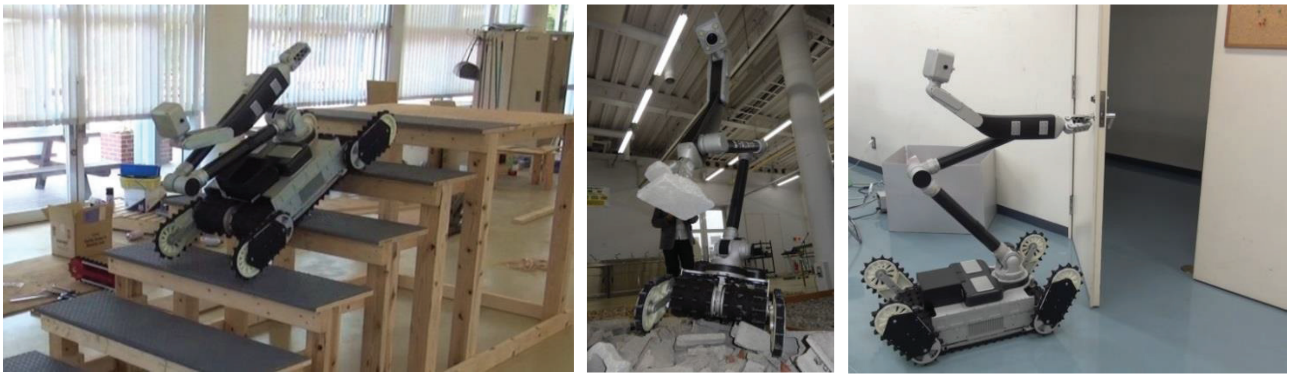

Fig. 9 Stair Climbing (left), Debris Removing (middle), Door Opening (right)

6 Conclusions

To enhance information-gathering ability of disaster response robots, a camera arm system is considered. From practical view points, mechanical design issues, such as functional requirements, space-effective designs and evaluation results, are discussed with revealed cross section drawings. As a future work, the hardware design will be further optimized by repeating more tight practicality tests, and the studies on stress-free remote operation interfaces are further continued.

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