Camera Arm System for Disaster Response Robots
(2nd Report: A Collision Protection Mechanism for Real-world Missions)

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Abstract

A collision protection mechanism, newly developed for a camera arm system of disaster response robots, is discussed. The arm system is mounted on remotely operated information-gathering robots that work at disaster site. The primary purpose of the system is to enhance investigating performance and to add light-work executing ability such as door opening to the previously developed robot, which has been used at the Fukushima nuclear accident. High mechanical robustness and user friendly control interfaces are inevitably required for the system to allow operations at inaccessible locations by remote control. After necessary specifications and hardware configurations are discussed, a collision protection mechanism equipped at joints of the camera arm system is explained in detail. Evaluation experiments of the arm system mounted on a newly developed crawler type robot "Sakura II" are also described.

Keywords: collision protection, manipulator, disaster response robot, rescue robot, mechanical design

1 Introduction

A newly developed camera arm system designed to install onto remotely controlled disaster response robots for disaster-site survey and light-work operation is described.

For the accident of Fukushima Daiichi Nuclear Power Plant caused by the Great Eastern Japan Earthquake [1], we developed a disaster response robot, named "Quince (nuclear power plant accidents response version)[2]." PackBot [3][4], made by iRobot corporation, was deployed into the reactor buildings at first. However, the narrow and steep stairs prevented its approach to the upper floors, and enough results were not obtained. Then, Quince with higher mobility than PackBot was sent into the reactor buildings, and its system improvements according to the opinions of on-site workers were repeated over and over. Consequently, Quince has achieved unmanned survey missions at the reactor buildings many times, and provided the significant information, leading to their cold-stop states [5].

In this project, for more detailed and tougher successive survey operations, we developed a new crawler type robot "Sakura II" and its camera arm system with collision protection mechanisms shown in **Fig. 1**.

Fig. 1 Developed camera arm system mounted on Sakura II

The robot is capable of more improved survey performance and light-work operation abilities. One of the most important characteristics of the camera arm system is collision protection mechanism for preventing from hardware breakage. Generally, there are two strategies for collision protection, *i.e.*, impact relaxation by mechanical designs [6] and impact absorption by compliance controls [7]. For impact relaxation, typical approaches include reduction of weight/inertia of the robot arm, installation of flexible joints, links and viscoelastic material covers. Main problems of these methods are decrease of the arm responsivity and difficulty of precise position control. Compliance controls require sensitive sensors and high speed control period, and these performances are critical to collision protection. The developed camera arm system introduces friction-type torque limiters in major joints. Because the torque limiter slips only when external excessive torque is applied, the proposed mechanism is capable of protecting joint mechanisms without the care of system responsivity, while precise positional controls of the end effector are allowed. Additionally, absolute joint angles are continuously readable even when the torque limiter slips.

In this paper, specifications of the developed camera arm system of Sakura II and a collision protection mechanism embedded in its joints are explained. In

Table 1 Specification of the camera arm system

Base Robot	Disaster response robot "Sakura II"
Equipment	- Network camera with a LED lighting unit - End effector for light-work
Basic functions	- Posture holding without electric power supply - Collision protection mechanism - Waterproof/dust-proof properties (IP67) - Constant detection of absolute joint angles
Links/DOFs	60[cm] (resizable) x 3 links / 8 DOFs
Payload	4.5[kg] (depends on torque limiter settings)
Weight	Total: 20[kg] (Arm: 16[kg], Arm Base: 4[kg])
Connections	Power: 30V, Network: CAN, Ethernet

particular, the collision protection mechanism is an important element not only for the enhancement of its mechanical robustness and reliability, but also for the alleviation of operator's anxiety about mechanical damages of the remotely controlled system through collisions against environments. System verification experiments of door manipulations by Sakura II with the camera arm system are also reported.

2 Camera arm system

2.1 System purposes and basic specifications

The purpose of the camera arm system is functionality enhancement of the disaster-site survey and the light-work operation. For this purpose, the camera arm system has to satisfy following requirements based on opinions of on-site workers.

(a) The size and weight of the camera arm system have to be suitable for Sakura II without deteriorating its mobility in inherently unknown irregular fields.
(b) The arm system must be able to change variedly its camera position and posture. A wide-angle and high-resolution camera with a LED lighting unit have to be mounted on the head of 2m length arm.
(c) An end effector for light-work operations such as door manipulations and sample collections has to be equipped.
(d) The arm system has to be sufficiently reliable against mechanical damages due to collisions to surroundings. Even in the case that unexpected collisions occur, the arm system has to be able to recover its operation immediately.
(e) Continuous working time of the arm system by internal batteries has to be satisfactory by power saving technologies.
(f) The system must not be affected by weathers and/or hydrothermal environments through its waterproof and dust-proof properties.
(g) Operators must be able to control the system without anxiety by reliable and stress-free remote control interfaces.

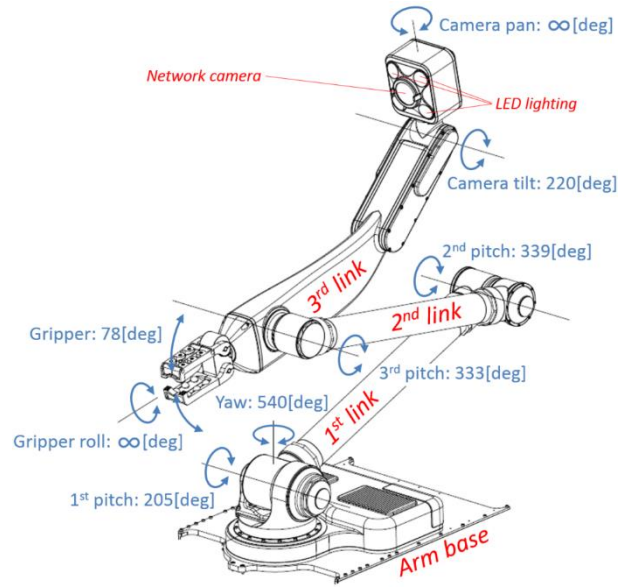Basic specifications of the developed system based on these requirements are summarized in **Table 1**.

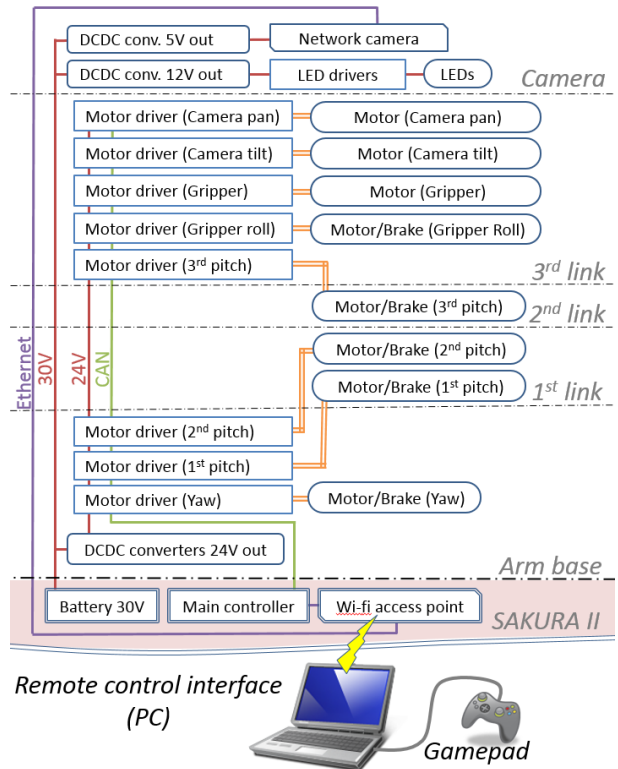**Fig. 2 Mechanical link structure, degrees of freedom and ranges of joint angles**

Fig. 3 Schematic diagram of the camera arm system

2.2 Mechanical structure and schematics

The system has three 60cm links and a network camera (AXIS Communications AB, 212PTZ) with a LED lighting unit at the head of the arm for satisfying the requirements (a) and (b). Three pitch joints of the arm are arranged on a yaw joint at the arm base. Furthermore, pan/tilt axes of the camera and opening/closing axis and roll axis of the hand gripper are equipped at the 3rd link (requirements (c)). The 3rd pitch joint is also utilized for

gripper pitching. These eight joints in total are connected by three links, made by the carbon fiber reinforced plastic (CFRP) with the bonded aluminum alloy parts. This mechanical structure realizes a lightweight body with high rigidity of the arm system. We maximize range of each joint angle for various postures of the camera arm system. In particular, the gripper roll axis and the camera pan axis are capable of infinite rotating [8], [9]. Basic link structure of the system, layout of DOFs and ranges of joint angles are shown in **Fig. 2**.

To promote the reliability against dust, humidity and water, all mechanical elements, such as motors, absolute angle sensors, motor drivers, DC-DC converters and their wire harnesses, are arranged in the inside of the arm body. Mechanical robustness, waterproof and dust-proof properties of the system are realized by these techniques (requirements (f)). Additionally, heat generated by motors, motor drivers and others is dissipated through heat sinks bonded on the CFRP pipes by unitary forming. The curved shape of the 3rd link is for viewing the gripping point easily from the mounted camera.

The schematic diagram of the electrical control system is shown in **Fig. 3**. A main controller, batteries and a Wi-Fi access point are installed into Sakura II, and they provide power and reference angles of all joints as control commands to the arm system. Because other components for the arm system are mounted into its body, it can be detached easily from Sakura II and work as an option part of disaster response robots. As a communication bus between the main controller and the motor drivers, controller area network (CAN) known as a robust field bus by differential voltage method on two twisted wires is used. All the motor drivers are then connected by its daisy chain configuration. The servo control of each joint can be easily and remotely disabled, so that passive joint motions are available without force sensors at backdrivable joints according to operator's intent. The arm system is remotely controlled by wireless connected PC with a gamepad. Collision protection mechanisms and posture keeping mechanisms of joints are discussed next.

3 Structure of pitch joints with collision protection mechanism

High mechanical robustness (Requirement (d)) of the camera arm system is significantly important to operate real-world missions. At the same time, several essential functions such as power saving (Requirement (e)) and waterproof/dust-proof properties (Requirement (f)) are required for successful missions in inhospitable environments. As a representative example, the 2nd pitch joint of the system is taken, and its mechanical structure that satisfies these requirements is explained below. Note that the 2nd pitch joint is an important joint to lift up the camera and the hand gripper and requires comparatively large drive torque.

A cross-section diagram of the 2nd pitch joint is shown in **Fig. 4**. Right half of the diagram indicates the 1st link side, and left half shows the 2nd link side. A motor with an electromagnetic brake enclosed in the 1st link is at the back side of the figure, where the axis of the motor is perpendicular to the joint shaft (see also **Fig. 5**),

and the motor torque is transmitted to the 2nd link through a bevel gear, a harmonic drive and a torque limiter aligned along the joint axis. The points of the mechanical design are explained in the following subsections.
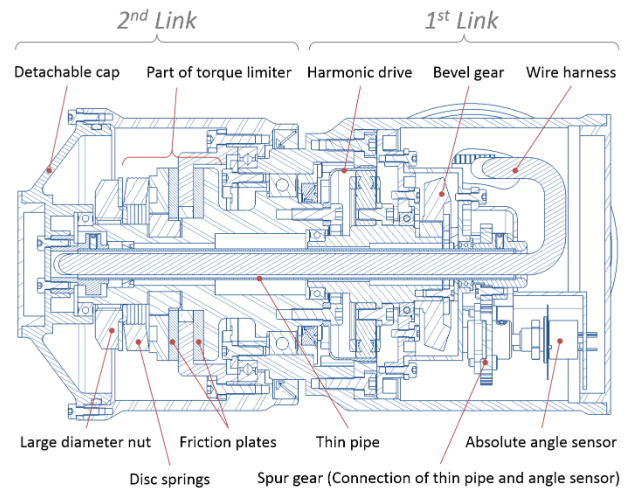

Fig. 4 Cross-section diagram of the 2nd pitch joint

3.1 Collision protection mechanism by torque limiter

Without torque limiter, impact forces can directly act to gear teeth of the harmonic drive, when the camera arm system unexpectedly collides to external environments. To protect the mechanics by reducing impact forces, a friction-type torque limiter is installed at the output of the harmonic drive.

As shown in **Fig. 4**, a flange fixed to the 2nd link is sandwiched between two friction plates of the torque limiter. These flange and two friction plates are tightened onto the output of the harmonic drive by a large diameter nut with disc springs. As verified in the experiment later, the slip torque can be adequately adjusted by tightening the nut that can be easily accessed by removing detachable cap of the joint.

3.2 Posture hold mechanism without power supply

Non-excitation type electromagnetic brake mounted on the joint motor axis realizes the non-power-supplied posture holding of the arm to enlarge the operation time. Because simultaneous moving of all the joints is seldom in real-world missions, the operating time of keeping the arm posture becomes considerably long in contrast with the time of actually moving. Therefore, a certain level of power saving effect is promised.

3.3 Wire harness passing through hollow joint shafts

We select a hollow structure for the main joint drive shaft consisting of bevel gears, harmonic drives and torque limiters. A merit of wire harnesses passing through the hollow joint shaft is that there is no exposure of wiring to the external atmosphere. Furthermore, wire bending due to the joint rotation is minimized by putting them through the exact center of the joint axis. The reliability of electrical components and their waterproof and dust-proof properties are promoted by this design.
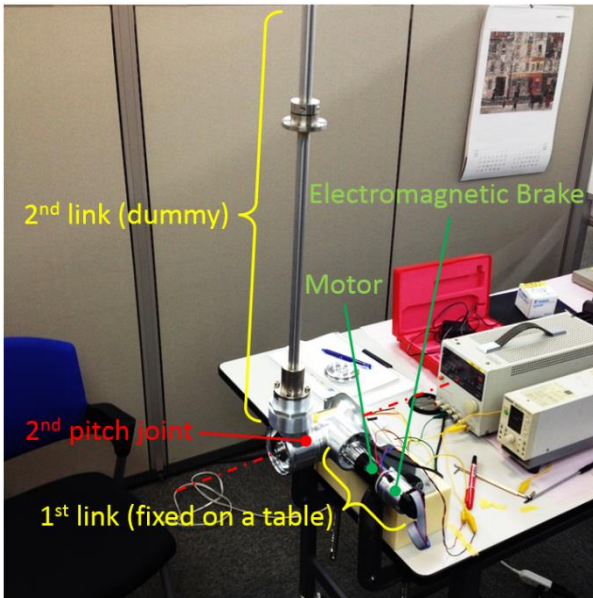
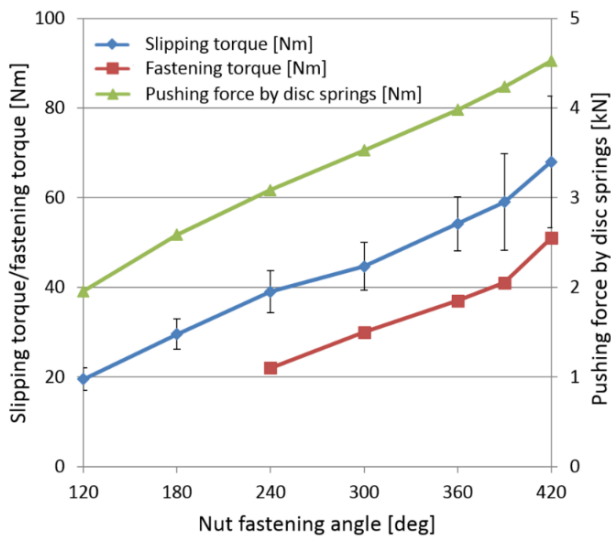**Fig. 5 Torque limiter testing device**

Fig. 6 Relationship between nut fastening angles and slip torques

3.4 Sensor layout for absolute angle measurement

At the time of collision, joints can be moved without motor rotations by slips of torque limiters. If absolute angles of joints are not obtained in such a case, an undesirable initializing process of the arm posture is required. Therefore, we devise a particular arrangement of angle sensors for obtaining absolute joint angles.

A thin pipe, fixed on the 2nd link and passed through the main hollow shaft, is used to deliver directly and mechanically the rotation angle of the 2nd link to the 1st link, where an absolute angle sensor is mounted on. Another important role of the thin pipe is that it works as a mechanical guide for wire harnesses passing through the joint shaft.
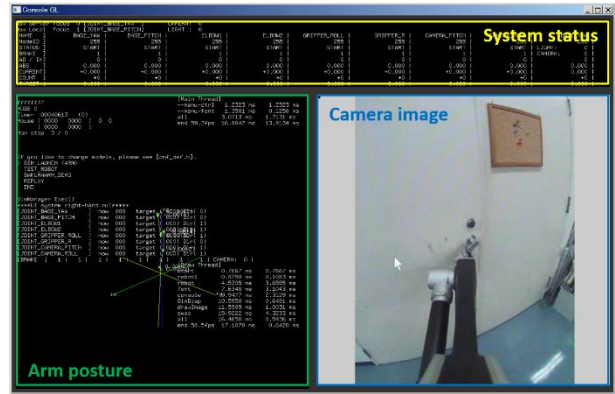

Fig. 7 The operation display of the developed remote control interface

4 Slip torque verification experiments

The function of the torque limiter is evaluated by a testing device shown in **Fig. 5**. One side (1st link side) of the testing device is fixed on a table, and a dummy 2nd link is mounted on the opposite side of the joint. A push pull gauge is utilized to measure forces acting on the dummy 2nd link at the moment of starting a slip. The rotation of the joint was fixed by an embedded electromagnetic brake, and slip torques were measured multiple times. Here, slip torques at the times of nut fastening and loosening were different because of hysteresis of friction in torque limiters. We chose the torques at the time of nut fastening and measured slip torques at various fastening angles of the nut within effective range of the disc spring deflection. The results of the experiment are summarized in **Fig. 6**.

As shown in **Fig. 6**, slip torques increase as the nut fastening angle increases. Fastening torques of the nut and pushing force by disc springs are approximately proportional to the nut fastening angle. The result also shows that variability of slip torques grows wider as the nut fastening angle becomes large.

These results indicate that we are able to adjust slip torques of joints according to intended tasks within the effective range of the disc spring deflection.

5 Door manipulation experiments utilizing remote control interface

We conducted verification experiments of door manipulation by the remotely controlled Sakura II with the camera arm system. The purpose of the experiments was confirmation of the system performance and operability. An operation display of the developed remote control interface is shown in **Fig. 7**, where the camera image, the current arm posture, the system status and other information are indicated on the operation display. The scene of the door manipulation task and the sequence of the operation displays are indicated in **Fig. 8** and **Fig. 9**, respectively.

The task sequence, consisting of grasping the knob, opening the door and passing through it, was achieved by the third trial, and its elapsed time for the whole task was about 4'20". By remotely switching the yaw joint servo control as active/passive according to the task progress,
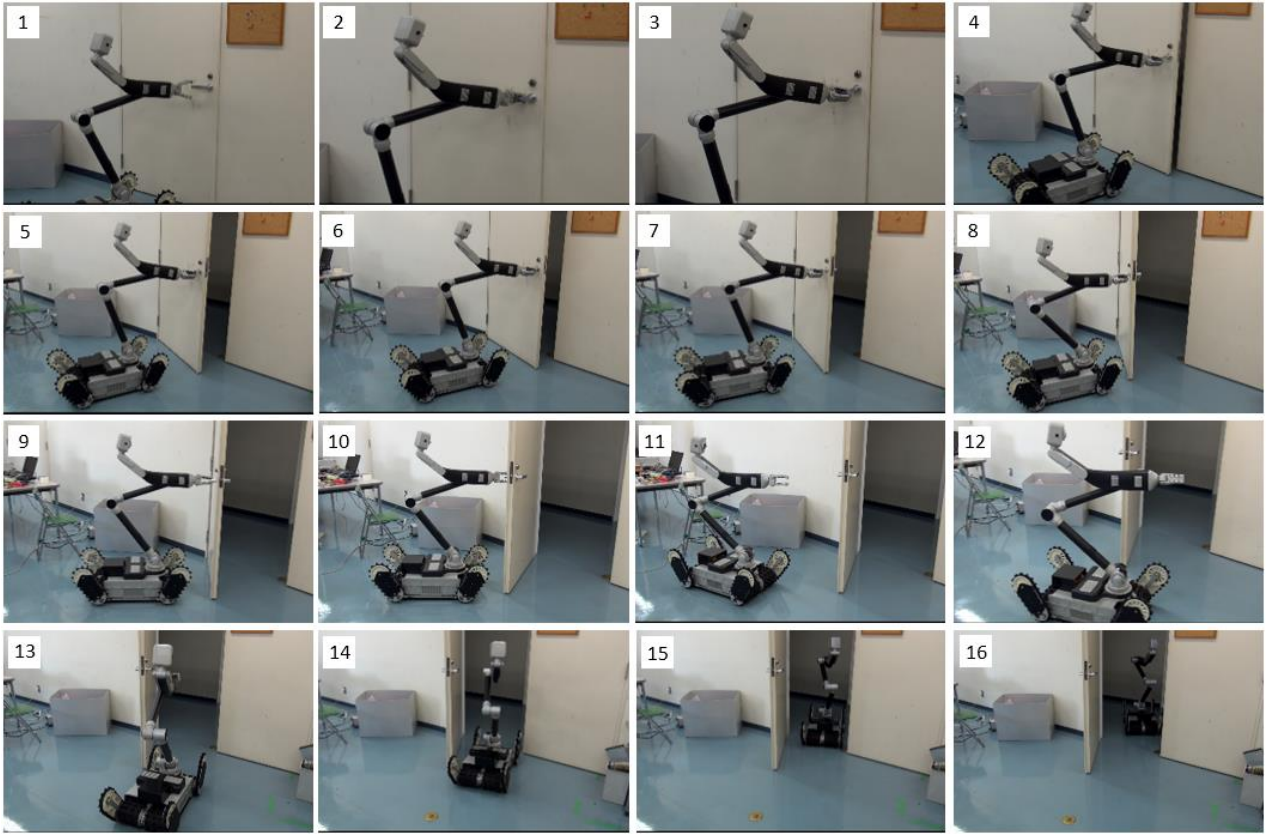
Fig. 8 Scene of the door open task: grasping the knob (1-3), opening the door (4-10), and passing through it (11-15)
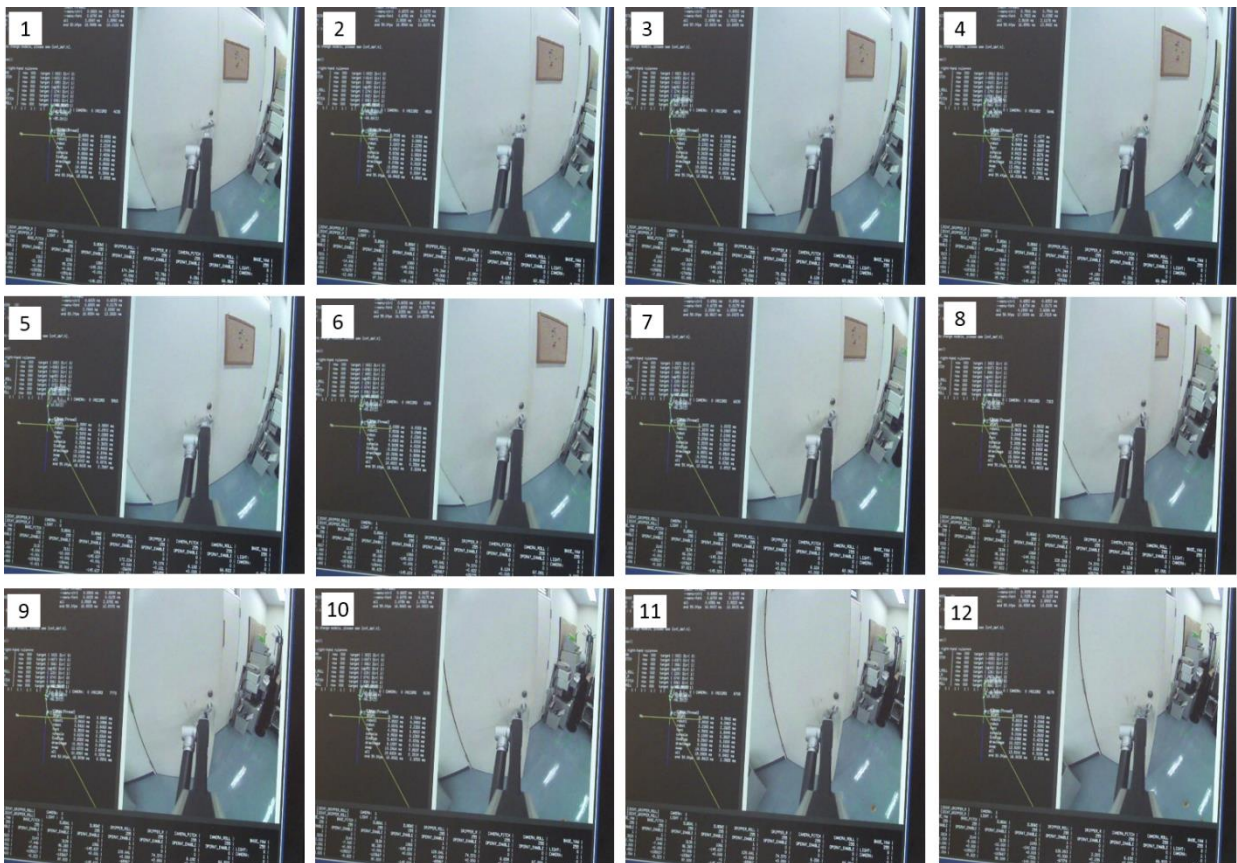

Fig. 9 Sequence of the operation displays during the door opening scene

the difficulty in the doorknob pulling could be greatly reduced. Another essential factor for the successful operation is that the operator stress against the mechanical damage due to collisions, such as contact between the door and the gripper, could be alleviated by the function of the properly configured collision protection mechanism. This fact suggests another applicability of collision protection mechanisms to adaptive joint motions to target objects or environments. Through the experiment, it is shown that the developed remote control system is capable of manipulating the door and passing through it.

On the other hand, there were mainly two reasons, where we had to retry (not many but several times) the door opening operation. First, it was hard to recognize the depth distance near the gripping point through the operation camera image. Second, there was difficulty to control the combined simultaneous motions of the camera arm and the crawler of Sakura II.
For the difficulty of the distance recognition, an approach to install secondary camera, for example a camera mounted on its hand, for additional view of the gripping point from different direction can be considered. For the second difficulty, currently, a gamepad button is assigned to completely switch the control mode among the camera arm and the crawler of Sakura II. We should develop also an interface that can easily operate the combined motions of multiple degrees of freedom systems.

6 Conclusions

In this paper, we described the camera arm system mounted on the disaster response robot Sakura II and its collision protection mechanism for real-world missions. In particular, the necessary specifications of the system for real missions and a mechanical structure of the pitch joint with the collision protection mechanism were explained in detail.

In experiments of the camera arm joint, it was verified that the slip torque was able to be easily and appropriately adjusted by nut fastening angle, which is used at the collision protection mechanism to gain the effective frictional dissipation of impulse energy. We also showed by door manipulation experiments the validity of the system regarding fundamental abilities such as information gathering and light-work execution, and verified the user friendliness against the mechanical damage due to collisions resulting from the collision protection mechanism. Through the operation experiment, we revealed further improvements regarding the operation interface, and listed them as future works.

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