Proceedings of FDR2024
International Topical Workshop on Fukushima Decommissioning Research
Oct 10-13, 2024. J-Village, Naraha, Fukushima, Japan

FDR2024-1011

DECOMMISSIONING ROBOT MANIPULATOR FOR FUEL DEBRIS RETRIEVAL

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Keywords: Fuel debris, Robot manipulator, Navigation, Gripper, Debris simulant, Machine learning

ABSTRACT

Fuel debris retrieval at the bottom of the primary containment vessel (PCV) is one of the significant tasks for the decommissioning of the nuclear power plant and in particular for 1F. It is challenging for conventional manipulators to perform the retrieval process due to the presence of radiation, water leakage, and poor lighting conditions. We tackle those problems with the design and fabrication of a novel mechanical manipulator and its control and navigation algorithm. CVT (Continuous Variable Transmission)-based actuation improves the robot's shock resistance. AI-based navigation algorithm enables semiautonomous navigation and grasping in the cluttered environment inside the PCV.

First, we investigated the shock-resistant mechanisms for the drive train and the gripper part. The drive train features CVT-VIA which utilizes the toroidal CVT for the adaptive gearing. In addition, the flexible debris gripper makes use of the spring joint instead of the conventional axial joint. The tuning of ligament allocation enables the designer to devise the spring joint with the arbitrary deformation characteristics.

Second, we developed a navigation system to overcome the obstacles. The human operator can control the robot end effector by clicking the target point from the vision input. The method features the ML-based approach to overcome the cluttered conditions.

Third, we validated the approach with a real-world experiment. The experiment was done at NARREC.

In conclusion, the decommissioning robot manipulator features the CVT-based actuation and a learning-based navigation system. Future works include the development of the whole manipulator with CVT-VIAs and the integration of the navigation system with the compliant actuators.

1. INTRODUCTION

The exploration of the bottom part of the PCV and retrieving fuel debris is still one of the most challenging tasks (Fig. 1). To accomplish the task of fuel debris retrieval in the PCV environment, we propose the robot system with shock-resistant hardware and obstacle-aware navigation software.

This research describes the hardware design of the CVT actuation part and the gripper part with the flexible joints. ML-based navigation is also devised for the intuitive operation.

The research contributes to the acceleration of fuel debris retrieval task via the handy manipulator system of mechanical robustness and the ease of operation.

The extended abstract is organized as follows. Section 2. explains the hardware architecture aiming at the shock-resistant robot structure. Section 3. illustrates the navigation software framework which exploits the machine learning techniques. Section 4. exhibits the result and the discussion of demonstration experiment conducted in NARREC. Lastly, section 5. mentions the conclusion.

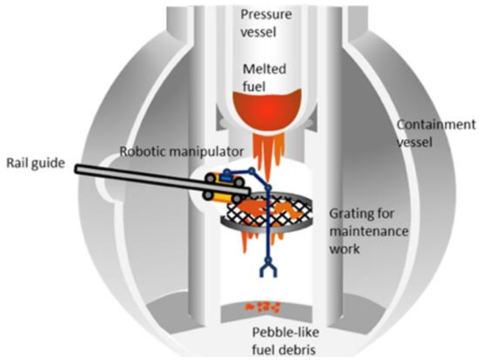

Fig. 1 Research concept

2. SHOCK-RESISTANT MECHANISM

The section explains the shock-resistant mechanisms of the proposed robot manipulator for fuel debris retrieval.

2.1 CVT-VIA AS DRIVE TRAIN COMPONENT

The PCV environment of 1F is the cluttered environment filled with the broken objects after the accident. Therefore, the robot manipulator has to go through the cluttered environment to achieve the retrieval task of the fuel debris at the bottom of the PCV. That is why the robot manipulator should be equipped with the shock-resistant mechanisms. For example, the drive-train components with the shock resistance enables the manipulator to fulfill the requirements of

(a) the precision for free space motion
(b) the adaptivity for unexpected collision.

VIA (Variable Impedance Actuator) is a promising actuation scheme to for the application. This study features the utilization of the Toroidal CVT.

CVT has been used for automotive application to achieve the smooth transition from the high-torque state to high-speed state depending on the driver's input. Toroidal CVT is composed of metallic balls, metallic discs and the traction fluid. The contact points between the balls and the discs change during the motion, which alters the gear ratio continuously. Fig. 2 illustrates the components and the test rig of the CVT-VIA. Especially, the research exploits the CP-CVT (Constant-Power CVT) (Cretu et al., 2005). The CP-CVT keeps constant output power by carefully designing the output disc. In other words, the CP-CVT changes the gear ratio depending on the output torque mechanically. In addition, the combination of the CVT and the specific planetary gears makes IVT (Infinite Variable Transmission). The input motor for the IVT does idling after the impact load torque on the output side, which protects the drive-train components from the impact.

The specification of the CVT-VIA has been determined from the requirements of the manipulator's dimensions (4.1 [m]) and the payload of 500 [g].

The collaboration research developed the CVT-VIAs of the following specifications (Parween et al., 2022).

- Gear ratio: 0.67 ~ 1.91
- Diameter: 20 [cm]
- Mass: 20 [kg]
- Traction fluid: Idemitsu TDF-1, 500 [mL]

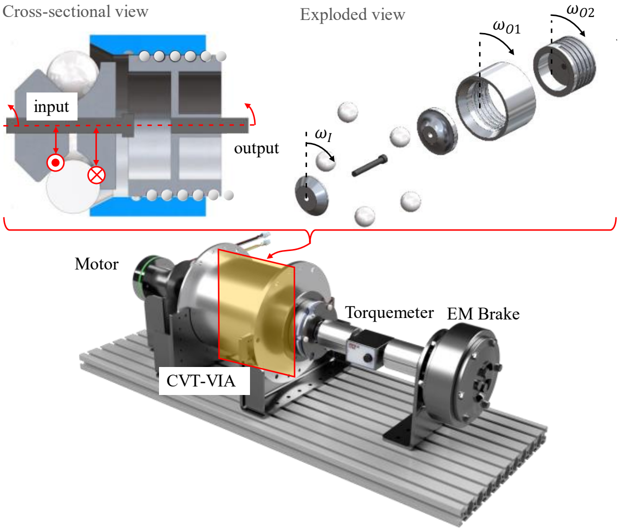

Fig. 2 CVT-VIA components and the test rig

2.2 GRIPPER DESIGN

Fig. 3 suggests the structure of the proposed gripper. we introduce a configuration with a multi-fingered gripper without axial joints for the purpose of structural robustness, adaptability to the grasped object, and prevention of structural destruction and release of the grasped object due to collisions. Based on relevant works (Makino et al., 2018; Hirose et al., 2022), we generated bending motion by utilizing helical spring joints and fiber constraints. Several computational design methods have been introduced using elastic resin structure for making robots (Megaro et al., 2017; Bosio et al., 2022), we adopt helical springs for its mechanical strength. Metallic helical joints have been utilized to not only grippers, but also multi-link spine for its mechanical robustness and simple structure. Spring parameter selection enables the developers to deal with divergent grasp objects.

A motor-driven tendon of polymeric wire "Dyneema" is mounted inside the finger structure and is wound by a brushless motor away from the gripper body. The adoption of the tendon drive system makes it possible to separate the drive source from the object to be driven.

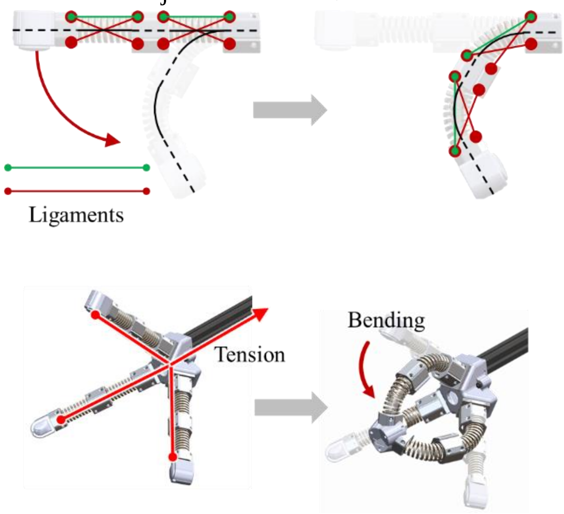

Fig. 3 Spring joint and the gripper

Because the spring deforms to any direction, proper attachment of the ligaments is necessary to output the desired motion. The study investigates the length change of the ligament wire depending on the spring's bending and twisting motion. It is assumed that the ligaments are restrained by the strings and cannot be lengthened beyond the length at which they are attached. On the other hand, the shortening deformation corresponds to the slack of the ligament. In the ligament, there are parallel ligaments and cross ligaments, each of which acts as a resistance to translational and rotational motions. Note that the initial length of the cross ligament is larger than that of the parallel ligament. In addition, because the ligament attachment is performed while the spring is stretched, the ligament cannot be elongated from the length by the spring's bending motion.

The bottom of the pedestal where debris exists is an environment where gamma rays and shallow water exist, and separating the minimum electrical components for driving from the main body of the gripper contributes to improving the waterproof and radiation resistance of this robot gripper.

Fig.4 demonstrates the validation experiment of the three-fingered gripper. The gripper performed the grasping motion and the underwater open-close motion without any failure.

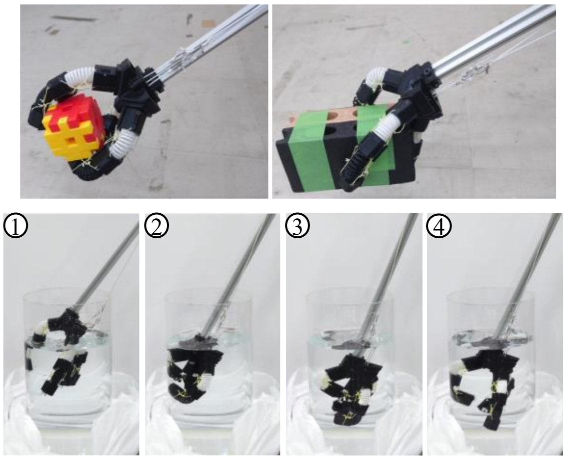

Fig. 4 Verification of the proposed gripper

3. NAVIGATION FOR OBSTACLE AVOIDANCE

The section states the navigation system for obstacle avoidance.

3.1 REACHABILITY ANALYSIS

We calculated the reachability of the manipulator using Algorighm 1.

Algorithm 1 Task Motion Planning

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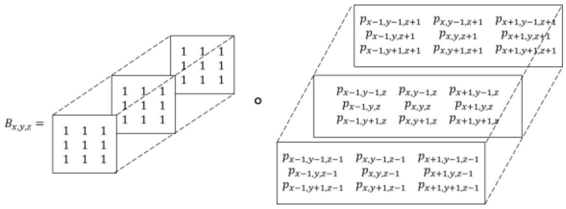
while $N_0 < max_0$
    while $N_1 < max_1 \quad \vee \neg\ (pathfound)$ do
        set random joint position P_1
        IK from the target proximity (5 iterations)
        if Collision or self-collision is not detected then
            IK from the target object - gripper (5 iterations)
            if Collision not detected and the object can be grasped then
                FK Interpolate motion from start to goal
                if Collision or self-collision is not detected then
                    path found = True
                end if
            end if
        end if
    end while
    IK from the rest position to P_1
    IK from the target position to the rest position
    if Robot or object collision or self-collision is not detected then
        Object is reachable
    end if
end while

We adopted Damped Least-Squares (DLS) for solving IK. The for loop was implemented with the condition (1).

$$max_0 = max_1 = 10 \tag{1}$$

The reachability was calculated using the weight value from (2) (3) (4).



(2)

$$w_{x,y,z} = \frac{1}{32}\|vec(\boldsymbol{B})\| \tag{3}$$

$$V = \sum_{x=1}^{m}\sum_{y=1}^{n}\sum_{z=1}^{p} w_{x,y,z} * l^3 \tag{4}$$

3.2 NAVIGATION SYSTEM

The navigation system facilitates the operation using the hand-eye camera information, and the Deep RL technique. As shown in Fig. 5, the navigation system is composed of

(a) Projection
(b) IK, planning
(c) Joint->motor transformation
(d) Motor output.

For (a), the operator utilizes the camera model which can be derived from the calibration sequence.
For (b), machine-learning-based approach was adopted. From the camera information and the operator's input, DDPG (Silver, D., et al., 2014) or SAC (Haarnoja, T., et al., 2018) determines the robot's target joint angle values. These values are sent to the robot controller PC via UDP.

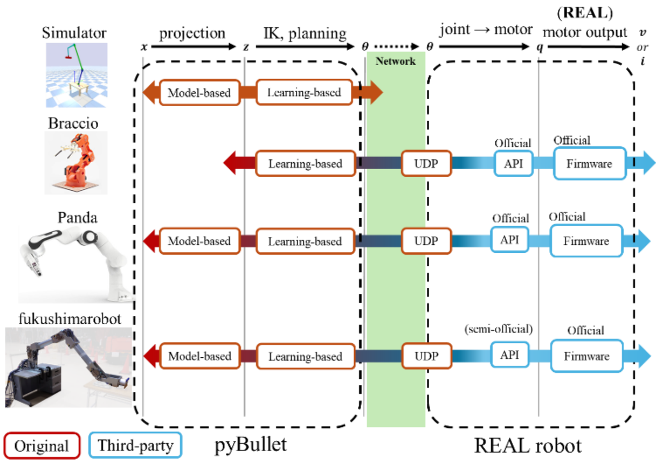


Fig. 5 Software architecture

Fig. 6 shows the navigation experiment on a robot arm.

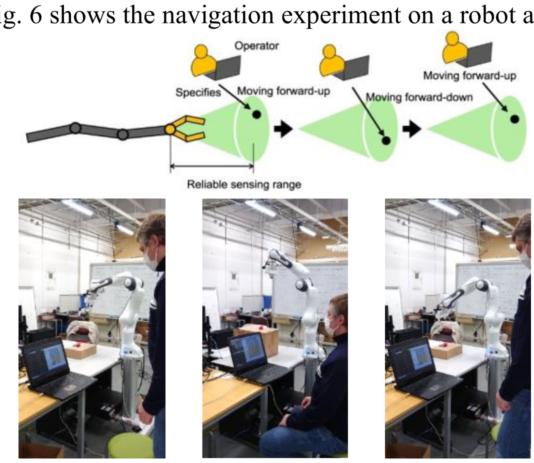


Fig. 6 Navigation experiment of life-sized robot arm

4. DEMONSTRATION

We conducted the demonstration of the navigation experiment at NARREC. Fig. 7 shows the operator PC. The operator clicked the target position from the camera view. The robot's end effector moved towards the target point.

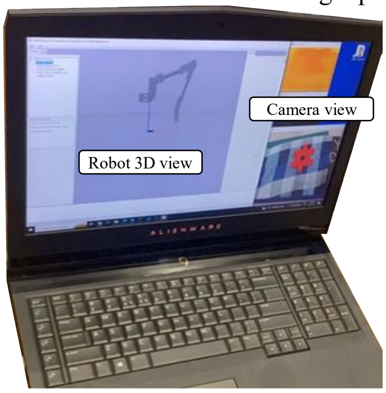


Fig. 7 Operator PC

Fig. 8 exhibits the teleoperation experiment at NARREC.

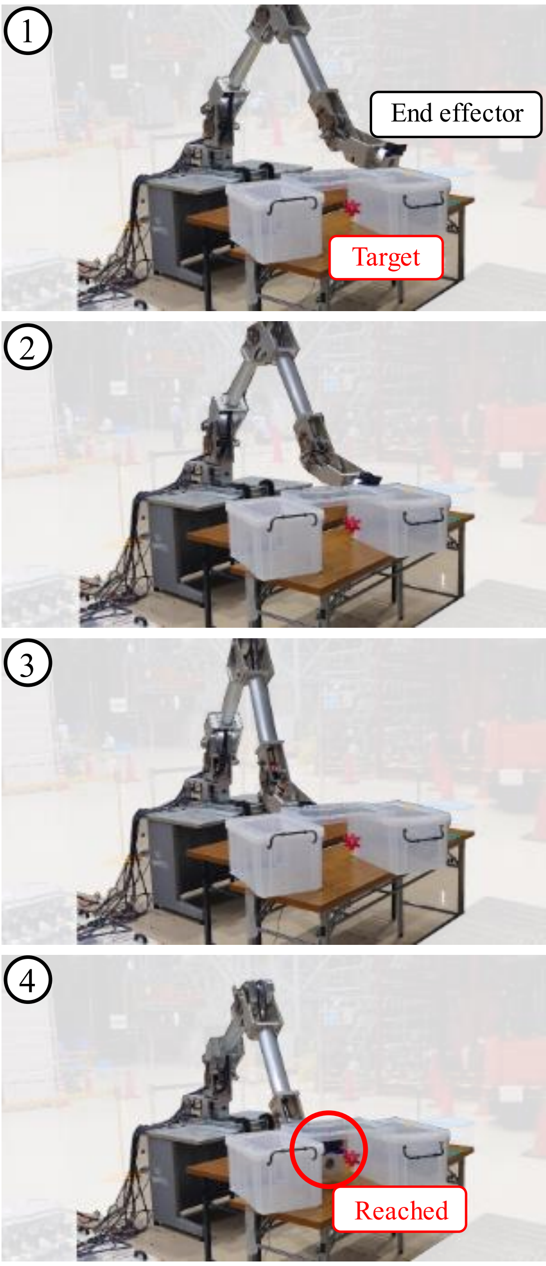


Fig. 8 Navigation experiment at NARREC

The robot moved with the operator's mouse commands. The operator decided the commands to the robot using the the camera view. The end effector of the robot was able to successfully bypass the obstacles by receiving the operator's input commands. The maximum angular velocity of each axis was 2 [deg/s]. The limit value enabled the operators to conduct the experiment without any safety issues.

In summary, the demonstration experiment validated the feasibility of the proposed navigation system in the real-world scenario.

5. CONCLUSIONS

The research aimed at the development of the robot manipulator system to accomplish the retrieval of fuel debris. The research theme had the two directions. One was the shock-resistant hardware development, and the other was the navigation algorithm for obstacle avoidance. As for the hardware development, the CVT-VIA and the springy gripper were devised. For the software development, the ML-based teleoperation system and the navigation system were devised. The feasibility of the software framework was successfully demonstrated in the real-world scenario.

ACKNOWLEDGMENTS

The Collaborative Laboratories for Advanced Decommissioning Science (CLADS), Japan Atomic Energy Agency (JAEA), had been conducting the Nuclear Energy Science & Technology and Human Resource Development Project. This study has been conducted in this project since FY2021. The authors acknowledge the members of Sussex university for their technical contributions.

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