Robots Technology for Decommissioning of Fukushima Daiichi Nuclear Power Stations

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Contents

- **Robots in Fukushima Daiichi**
  - Missions depending on phases
  - Failures & Countermeasures

- **Requirements for Robots**
  - Fundamental requirements for robots
  - Characteristics of robotics for NPP
  - Fuel Debris Detection Technology

- **Developed/-ing devices for decommissioning**
  - Sequence of Fuel-debris retrieval
  - Fuel Debris Retrieval Technology
  - Subsystems of an investigating system
  - Required technology in robot system

- **Design criteria for robots**
Robot technology for decommissioning

The difficult targets are
- to retrieve fuel-debris
- to prevent leakage of radioactive substance
- to prevent re-criticality,

under the severe conditions such as
- unknown, undefined environment
- high radiation level
- water, high humidity, existing hydrogen
- complicated obstacles
- large, and heavy mechanisms
- small experiences of operations

Approach to R&D of robots
- to utilize knowledge of robotics
- to introduce the improvements
Missions depending on phases

Phase 1: Emergent Situation: Cooling down of reactors
Phase 2: Stabilization: Containment and systems reconstruction for aftershocks
Phase 3: Decommission: Fuel removal

Uncertainty of objects & purposes

Emergent countermeasure

Phase 1: Emergent countermeasure
Phase 2: Investigation and appropriate measure
Phase 3: Full-scale development

by H. Asama
by Y. Yokokohji

Existing devices
Combination of established technology
Development of devices suitable to the site
Phase 1

Procure off-the-shelf robots and equipment (for general purpose)

Putzmeister Concrete Pump Truck

Remotely Controlled Construction Machines

Honeywell T-HAWK

iRobot Packbot

iRobot Warrior

QinetiQ Talon

QinetiQ Bob Cat

Brokk-90

Brokk-330
Phase 2

Remodel developed system and technology

Quince
Quince 2
Quince 3

Gamma-ray Measurement Robot

JAEA-3

Sakura
Rosemary

FRIGO-MA
Survey Runner

ROV

Quadruped Robot & Inspection Robot

ASTACO-SORA

MEISTeR

Inspection Robot Of upper part of S/C

Manipulator for Robot Set-up

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Phase 3

New development (for specific use)

- Robot for Decontamination
- Inspection robot for high location
- Water Surface Inspection Robot
- Inspection Robot for Lower part of S/C
- PCV Inspection Robot Scorpion Robot
- PCV Inspection Robot Mini Mola Mola
- Robot for Measurement of S/C Water Level
- PCV Inspection Robot PMORPH

by courtesy of Prof. Asama
Failures & Countermeasures

Failures

- Insufficient specification/Unknown environment
- Prototypes without improvement
- Operation errors
- Wire handling
- Lighting and vision
- Device failure: communication, malfunctions by radiation

Countermeasures

- System management: collaboration among R&D+E&C teams
- Design: by frequent design reviews, risk assessment
- Simulations: to estimate effects, time, total quantity
- Mock-up: operation training, severe setting of environment
- Site measurement: point clouds of real environments
Lessons Learned from the TMI Accident

- Successful robots were
  - compact with simple function,
  - easy-to-use and easy-to-maintain,
  - easy-to-modify according to the needs of the site
  - common mobile platform

- High-function, large-sized robot was not eventually used

- Development of new robots should be planned carefully because the situations on the site may change.
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Robots newly developed for **Investigation of inside PCV**

**Two types of shape-changing, remote-controlled, crawler robots for investigation**

- **Investigation of outside the pedestal (Unit 1)**
  - When driving the narrow part
  - Advancing direction
  - Crawlers (two units)
  - Camera for guide pipe units
  - Shape changing

- **Investigation of inside the pedestal (Unit 2)**
  - Thermometer
  - Dosimeter
  - Camera for investigation
  - During investigation
  - CRD rail

- **Investigation of inside the pedestal (Unit 3)**
  - Front camera
  - Up-down thruster
  - Hanging camera on extension rod
  - Driving thruster
  - Light

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Sub-systems of robot technology

- **Brain (Remote control)**
  - **Sensor** (Camera, 3D sensor)
  - **Effector** (Manipulators, Tools)

- **Environment**
  - **Objects**
  - **Obstacles**
  - **Mobility system**

- **Operating room**
  - Measured data & Control signals
  - Power supply

- **Enclosure**
  - **Collection device**
  - **Arm type access equipment**
  - **Fuel debris**

- **RPV**

- **PCV**
Challenges on Robotics for decommissioning

- **High doze rate**
  - Weakness of Sensor-Brain-Effector system
    - **Radiation-hardened** electronic devices
    - Sufficient shields onto electronic devices
    - Mechanism without electronic parts
  - Prevention of contaminated parts
    - Washable and fully covered wires, like robots for food industry

- **Long/large in size and heavy in weight**
  - Low natural frequency of long beams, thus low controllability
  - **Encapsulations** of devices become much larger and heavier
  - Joining devices with heavy cells is required
  - Mock-up needs space and cost
  - Long **turn-around time** of improvement

- **Undefined environment and objects**
  - No light, high humidity, many obstacles
  - Unknown characteristics of handling objects
Fundamental requirements for robots

- Radiation resistance
- High Reliability, Maintainability, Easy-to-operate

Great amount of debris and obstacles
Large thus heavy machines

For retrieval of fuel-debris, large & heavy robots are required to cut and handle debris and obstacles.

Retrieval system for debris & obstacles

Maintenance & Supporting work

Maintenance tasks may change according to the retrieval devices, sensors. The robots need to have longer life-time.

Robots for investigation are as small as it can go through small penetration, to prevent radioactive leak.
Characteristics of robots:
• Large in size, heavy in weight
• Low natural frequency at TCP

Industrial robots

- Assembly robot: Reach 1.2m, **Ratio ≈ 0.21**
  Payload 10kg, Own weight 48kg
- Large-size robot: Reach 2.9m, **Ratio ≈ 0.20**
  Payload 600kg, Own weight 3,035kg,

Robots for Fukushima *

- Investigation arm: Reach 17.7m, **Ratio ≈ 0.052**
  Payload 54kg, Own weight 1,053kg
- Heavy handling robot: Reach 5m, **Ratio ≈ 0.125**
  Payload 100kg, Own weight 800kg

*The robot working inside the PCV has the risk of stuck due to failures. In view of such a risk, robots should be designed with a size that can be rescuable.*
Purpose of data sensing

Remote-control

- to **estimate** and **calibrate** the pose of sensors
- to detect the motions
- to introduce **maximum likelihood estimation**

High dose radiation

- to detect **the leak out** of radioactive substance
- to measure **the amount of fuel debris to excavate**
- to **record** the process of fuel-debris retrieval

Diagram:

- Position & 3D Measurement
- Radioactive Sensing
  - Sensor Fusion
- Action
  - Inventory & History
  - Time-log & Space-map
Strategies for Countermeasures against Radiation

**Shielding**
- Shield by lead/steel/tungsten (not realistic)
- Lead glass

**Radiation-hardened devices/components**
- Radiation-hardened(resistant) Semiconductor
- Camera tube(Hamamatsu Photonics) 2MSv dose
- Radiation-hardened Camera (SONY) 1000Sv dose

**Robust design(Fault-tolerance/ Maintainability)**
- Redundant and functionally degradable
- Modular design and easy replace

**Mechanical systems**
- Wire-driven/Tendon-driven
- Hydraulic drive(Water)

by courtesy of Prof. Asama

Rad-Hard devices

Redundancy

Robustness

Maintainability

Complexity

Weight-Size Constraints

Cable dis/connection
Development of radiation tolerant image sensor

- Vacuum type flat image sensor with 2D matrix electron source

See Y. Gotoh et al., FDR2019-1099

Photoconductor:
- little degradation except coloring of glass

Electron source (FEA):
- little degradation of insulating layer

Changes in photovoltaic properties

Changes in current-voltage characteristics

Y. Gotoh et al., IVNC2016 p.20.

by courtesy of Prof. Gotoh
Radiation-hardened mechanism

- **Flexible Structure Arm (Muscular Robot)**
  - Control devices are located outside of the high radiation area, and connected to the cylinder by a tube.
  - Joint: 4 water hydraulic cylinders and springs
  - Elongation of a cylinder causes the joint to bend
  - Elasticity prevents unexpected malfunction caused by collision.
  - Hitachi GE and Chugai Technos have developed five types of robots using 1 to 4 joints.
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Sequence of Fuel-debris retrieval
Collection, Transfer and Storage of Fuel Debris

Canister design
- High fuel exposure and enrichment \(\rightarrow\) high reactivity
- MCCI \(\rightarrow\) hydrogen generation caused by core concrete interaction
- Injecting sea water, melting cable \(\rightarrow\) effects caused by salt and impurities

Transfer (Dry–side access method)

1. R/B
2. Maintenance cell
   - Storage cell for fuel debris retrieval
3. Carry-out port (additional)
4. Transport cell
   - Handling cell for a storage canister
   - Washing a canister in a transport cask
   - Storing canister in a transport cask
5. Fuel debris transport building
6. Storage facility
7. Carrying out a transport cask
Fuel Debris Retrieval Technology

A side access method (image)

- Equipment cell
- New opening
- Biological shield wall (BSW)
- PCV
- Seal with BSW-PCV
- Sealing with the shielding wall (BSW) and the primary containment vessel (PCV).

Equipment transfer cart
Wastes transfer cart
X-6 penetration
Wastes transfer system
Pedestal opening
Pedestal

New opening

- e.g. a robot arm
- e.g. cutting technology (Chisel)
Fuel Debris Retrieval Technology: An example
Subsystems of an investigating system

Arm Type Access Device

- An arm type access device has been produced, which can access on a wide range through a penetration (X-6) of PCV.
  - Total length of the arm: Approx. 22m
  - An investigation device up to 10kg can be loaded.

*An alternative tool can be mounted.*
Subsystems of an investigating system
Access Route of Arm Type

- Connecting structure of primary containment vessel (PCV)

The connecting structure with the following functions has been developed.

- **Remote-operated** function with approaching/attaching an existing penetration flange
- **Seismic resistance** of grasping mechanism
- **Confinement** function
- **Maintaining** arm transmission
Subsystems of a retrieval system

Access Tunnel

- The access tunnel is required to connect a heavy-lift tunnel (approx. 800 ton) with PCV through the precise position control system from outside the reactor building.
- Delivery technology for curved heavy-lift tunnel in narrow space has been developed with the technology experienced in bridge constructions.
Fuel Debris Retrieval Technology
Removing Interfering Objects(image)

- Various pumps and other structure must be removed.
- A large amount of rubbles have accumulated in the pedestal.
- Technology for removing the interfering objects has been developed.

Image of element test of removing interfering materials
Removing Interfering Objects

at 10x speed/ total 1m22s
Required technology in robot system

- **Operation**
  - Simulator & VR
  - Human interface
  - Team training

- **Investigation**
  - Shape measurement
  - Radiation measurement
  - SLAM

- **Assembly/Disassembly**
  - Insertion, fitting
  - Holding parts

- **Cutting/Coring/Separation**
  - breaking fuel debris
  - Removing Interfering objects

- **Transportation**
  - Long transportation of heavy cells in radiative env.
  - Precise connection/mantling/dismantling

- **Brain** (Remote control)
- **Sensor** (Camera, 3D sensor)
- **Effector** (Manipulators, Tools)
- **Environment**
  - Objects
  - Obstacles
- **Mobility system**
- **Operating room**
- **Power supply**
**Four kinds of robots**

- Investigation (remote control)
- Retrieval system (remote control + semi-automatic)
- Maintenance robots (remote control + automatic)
- **Mounting robots** (remote control + semi-automatic)

![Diagram showing four kinds of robots based on size and radiation level](image)
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- **Design criteria for robots**
Machines for nuclear plants are designed as it works in slow, secured motion.

When machines are large (\(\ell\)), its weight is in proportional to \(\ell^3\), and required torque \(\ell^4\). Therefore, largeness in size causes various problems.

Industrial robots and humanoids are designed as intelligent and adaptable as human to the change of requirements and environment. Thus, higher flexibility is embedded.

When one ability must be improved, the other often turns worse. By taking zig-zag changes, both ability will be improved.
Machines in nuclear reprocessing plants can be dedicated to a specialized task. But decommissioning in Fukushima Daiichi needs to have **higher productivity** because of **huge amount of fuel debris** and other structural materials.

To achieve it, machines should be rearranged and improved in **good balance of the three axes; reliability, flexibility and productivity**.

An initial machine should be **simple enough**, then **zig-zag improvement** must be introduced.

The effect of size and weight must be taken into account.
Summary

- **Radiation-hardened devices** are key issues for robots for decommission.
- **Size and weight** cause various problems in remote control: long *turn-around time* of improvement and cost.
- **Training of operation teams** is the most important key for remote control.
- Balance of **reliability, flexibility** (multi-function), and **productivity** must be well-designed in the development of robots.
Thank you for your kind attention

Decommissioning of Fukushima Daiichi NPP is an epoch-making and historical project.
Let us watch, understand and memorize the project.

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