Disaster Response Robot Quince and Lessons at Fukushima-Daiichi Nuclear Power Plant Accident

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Japan MEXT DDT Project on Rescue Robots

FY2002-2006, PI: Prof. S. Tadokoro, Intl. Rescue System Inst., Budget: US$20M

Information Integration

Protocol and Database

- Protocol standardization (MISP)
- Disaster info. database (DaRuMa)
- Network integration and operation

Overview Info. Gathering

Surveillance from Sky

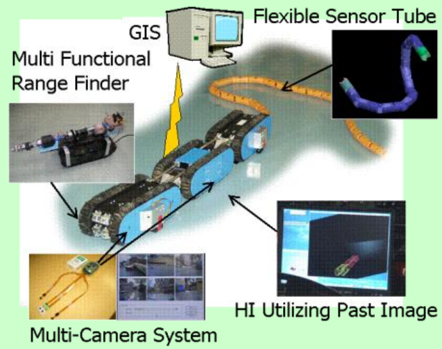
- Small-size helicopter (automatic surveillance)
- InfoBalloon (monitoring from fixed points)

Distributed Sensors

- Rescue Communicator (victim search sensor)

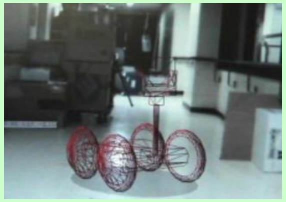
Advanced Rescue Instruments

Surveillance in Rubble Pile



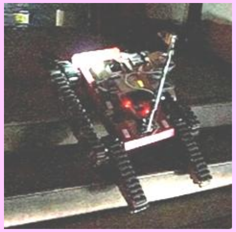
- ActiveScope Camera
- Integrated serpentine robot
- Rescue tools (jacks, search cam, power tools, etc.)
- Wireless triage tag (for rescue logistics)

Surveillance in Underground



- Integrated UGV
- Connected mobile mechanism
- Jumping robot
- Human interface for teleop. (virtual bird-eye view, 3D map, standardization, etc.)
- UWB human body sensor
- Adhoc network

Verification, Training, Demonstration



- Tokyo FD training site
- Niigata Chuetsu EQ.
- JICA Intl. Rescue training
- FEMA training site
- Collapsed House Simulation Facility in Kobe Lab.
- Firefighters unit, IRS-U

Confined Space Inspection

Active Scope Camera

Normal Video Scope

Stop in the middle ×3

Active Scope Camera

Move through the whole passage ×3

Active Scope Camera Deployment to Construction Accident in Jacksonville

(Tadokoro, Tohoku U
Murphy, USF)

- Jan. 4-5, 2008 @ Jacksonville, FL
- Gathered evidence info. 7 m deep
  - Shape & direction of RC cracks
  - Shape & cross section of flakes
  - Image of spaces inside
- Impossible by other equipment
  - size, mobility, controllability

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CRASAR-IRS Deployment to Cologne Historic Archive Collapse

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Cologne, Germany, March 6-8, 2009

- Search for 2 victims
- Standby for 3 days
- Operation from rubble pile 30 m high was too risky.

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Inspection of Pipe with 12 Elbows

With 12 Rectangular Elbows

Straight Pipe

Industrial application for aging facilities and infrastructure

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Date in 2011	Major Activities	Target	P in C
3/11	US: Request to CRASAR for deployment (Invitation letter: 3/17)	Collapse	ST
3/13	Sendai: ASC standby with Sendai City FD	Collapse	ST
3/14	Sendai: Call for robot needs to METI Tohoku and local governments Sendai: Quince standby	Factory Factory	ST EK, ST
3/15	Sendai: Airport investigation	Tsunami	ST, EK
3/17	**Chiba: Quince development for Kashima Petrol Plant** **Chiba: Quince development for Fukushima Nuclear Plant**	Factory Nuclear	EK EK, ST
3/19	**Hachinohe: KOHGA building inspection**, Needs in ports	Collapse	FM
3/28	**Sendai: Quince collapsed building inspection**	Collapse	ST
3/31	Iwate: Call for port inspection	Port	FM
4/2	Minami-Sanriku: Request for port inspection by mayor	Port	TK
4/7	Miyagi: Call for port inspection	Port	MM
4/11	Miyagi, Iwate: Call for digital archive	Town	MM
4/12	**Sendai: 3D & thermo camera for JAEA Vehicle**	Nuclear	ST
4/18-19	**Watari: Anchor Diver III port inspection**	Port	SH
4/18-19	**M-Sanriku: Seamore, SARbot port inspection w CRASAR**	Port	RM, TK
4/20-22	**R-Takada: Seamore, SARbot port inspection w CRASAR**	Port	RM, FM
4/29-5/1	**Ohtsuchi: RTV found 2 victims in sea**	Sea	TU
6/24-10/20 (6 times)	**Fukushima: Quince in Fukushima-Daiichi Reactor Bldg.**	Nuclear	EK
7/28-8/1	**Sendai: Quince & Pelican collapsed building inspection**	Collapse	VK, ST
10/23-25	**M-Sanriku: Seamore, SARbot port inspection w CRASAR**	Port	RM, FM

Red: Disaster Application
Green: Preparation

Unit 4 on April 7, 2012

Cask Storage on April 7, 2012

Operation Floor (5F) of Unit 4 on April 7, 2012

Needs for Robots in Fukushima Daiichi

- Missions
  - Stabilization of the system (Cooling and confinement)
  - Decommission (Extraction of nuclear fuel)
  - Minimization of radiation exposure of workers
- Tasks
  - Debris clearing
  - Surveillance and mapping outside and inside of the buildings (images, radiation, temperature, humidity, oxygen concentration, etc.)
  - Instruments setup, sampling
  - Shield and decontamination, etc.
  - Material transportation
  - Construction of pipes and equipment

Mobile Robots Packbot (Remotely controlled)

From Apr. 17

Packbot

Entering from the doors

Near Doors

1st floor of R/B Unit 1

1st floor of R/B Unit 2

1st floor of R/B Unit 3

TEPCO

Operation of Quince at Fukushima-Daiichi

June 26 - Oct 20

- Why Quince?
  - Higher mobility than other robots - for 2nd to 5th & B1 floors
  - Visual inspection by its HD camera
  - 2D/3D map generation
- Pros and Cons

Robot	Reliability	Communication	Radiation tolerance	Mobility	Mani-pulator	Camera
Quince	Good	VDSL (twisted pair cable) wireless LAN	Good	Excellent (2-5F)	Good	HD
Packbot	Excellent	optical cable wireless	Good	Good (only 1F)	Excellent	SD
Brokk	Excellent	cable ??	Excellent	Affordable	Excellent	??

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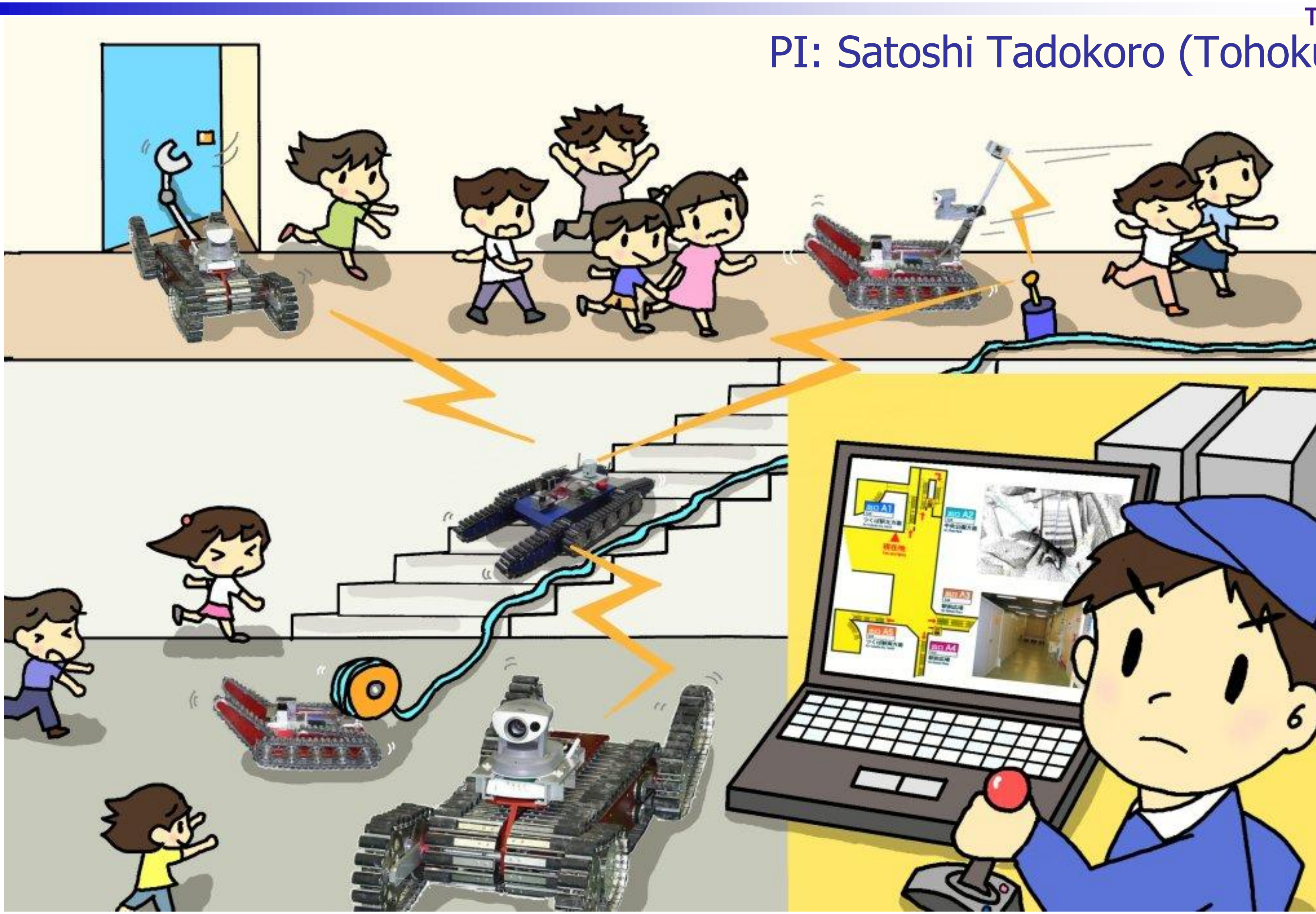
NEDO Strategic R&D PJ on Advanced Robot Components
High-Speed Search Robots for Confined Space

PI: Satoshi Tadokoro (Tohoku U)



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NEDO Strategic Robot Component Tech. PJ

Search Robots for Confined Space (2006-2010)

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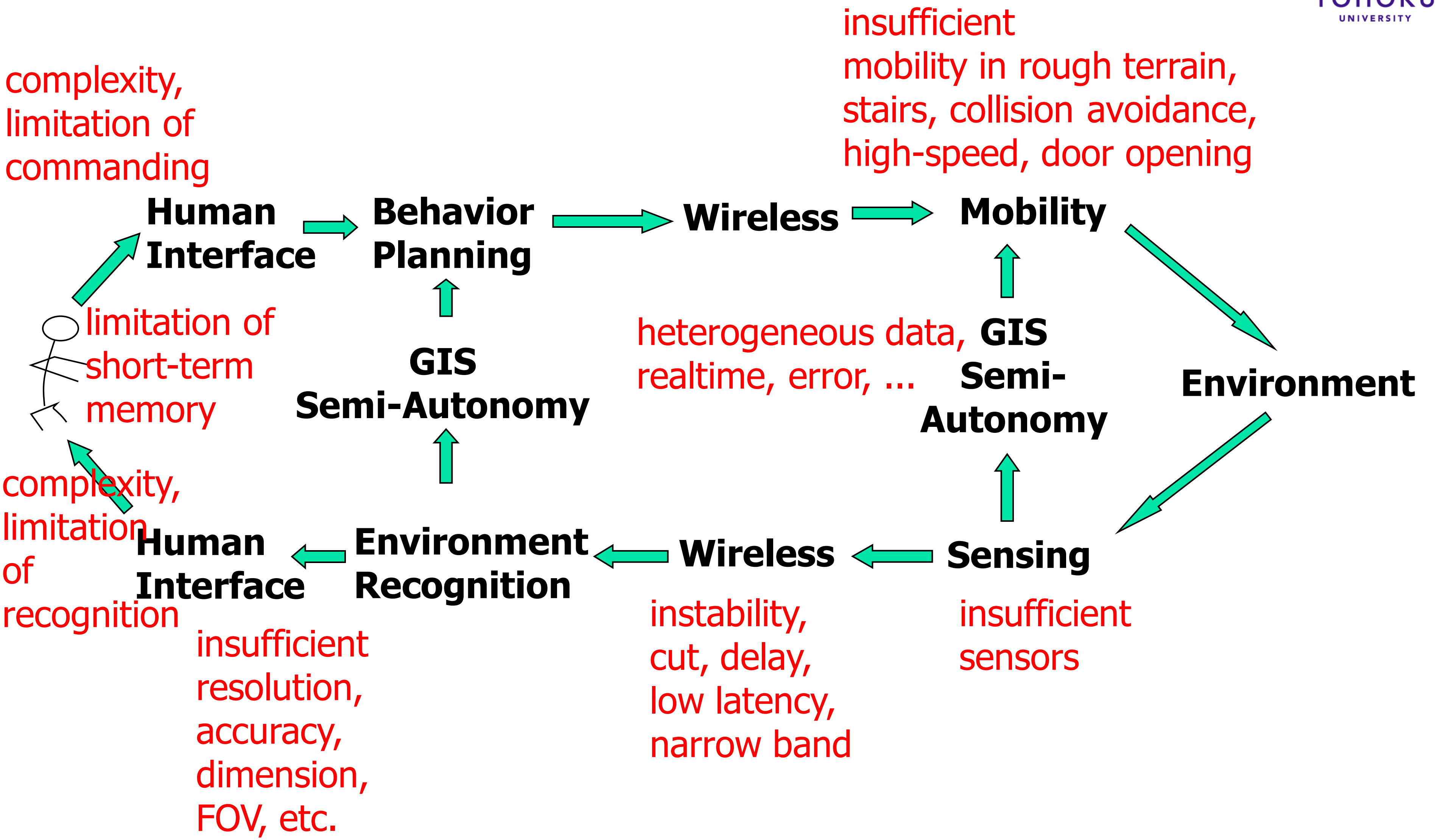

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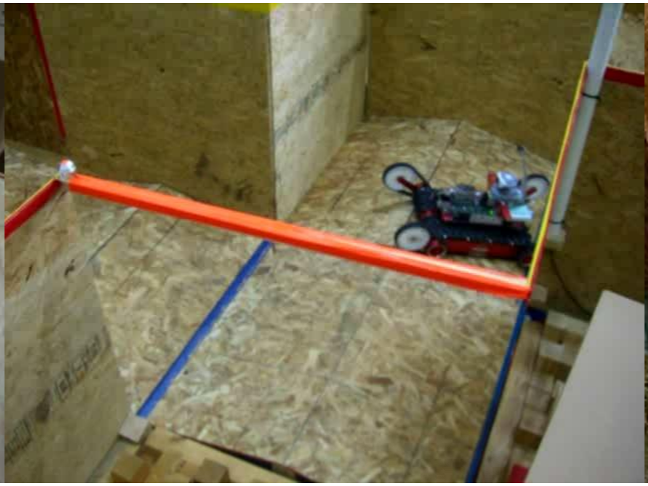
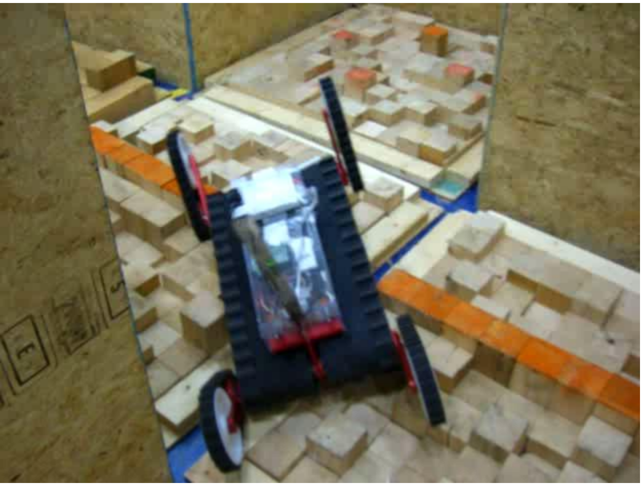
Tad Lab

Kenaf: Mobility Challenge Champion @ RoboCupRescue 2007 Atlanta and 2009 Graz





Kenaf showed the best mobility in the world using the NIST rescue robot evaluation field, which is proposed as international standard by ASTM.

Experiments @ E-Defense (Oct. 27, 2009)

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3 story houses collapsed

Mobility at collapsed roof

Entry into collapsed house

Mobility on beams of roof

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NEDO Strategic Robot Component Tech. PJ

Search Robots for Confined Space (2006-2010)

"Quince" at Disaster City (3/9/2011)

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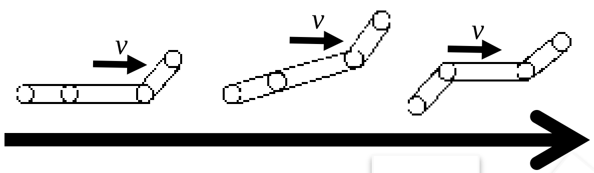
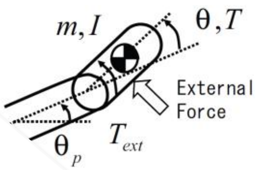
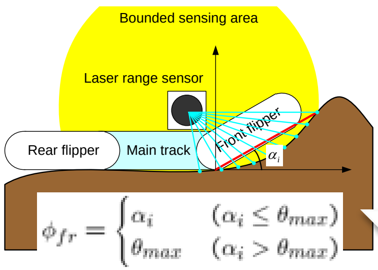
Operator Support by Semi-Autonomy



(1) By Using Touch Sensors
+ Distance Sensors



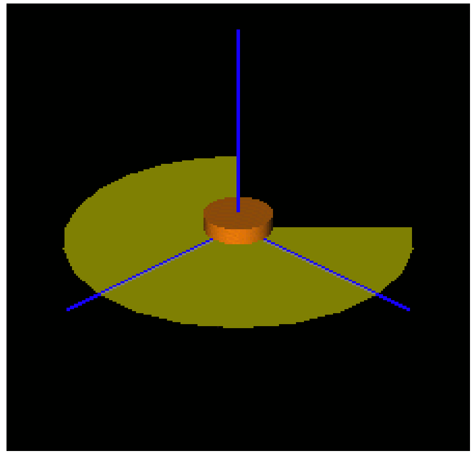


(2) Based on Measurement of
Terrain Shape by Laser Range Finders

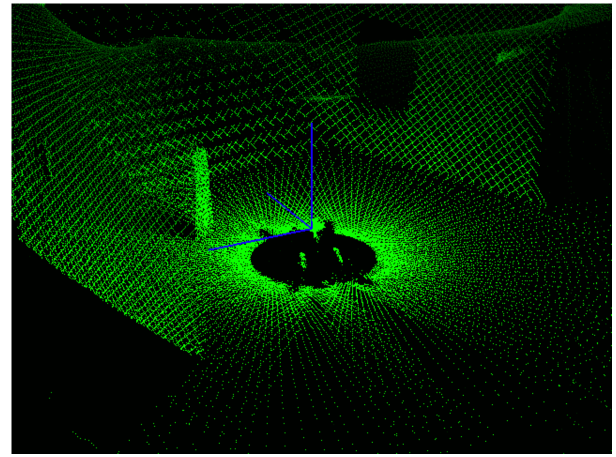
3-D Mapping

3-D laser scanner for dense point could

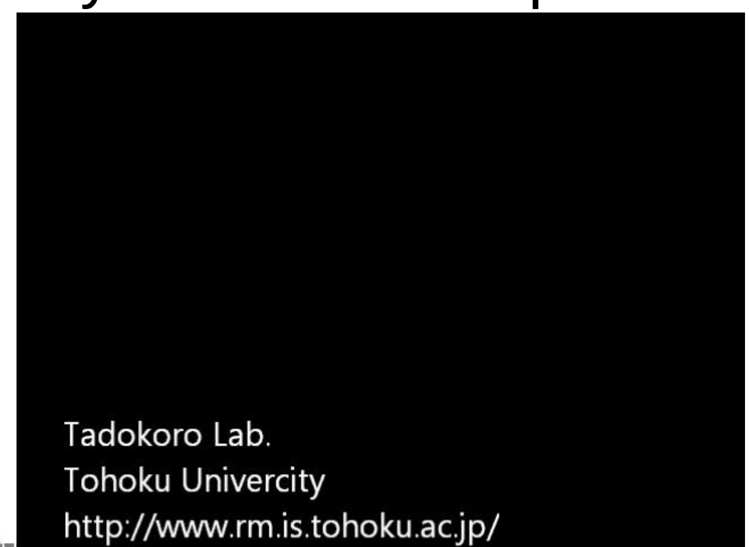
HD Scanner



Laser Trajectory



3D Shape



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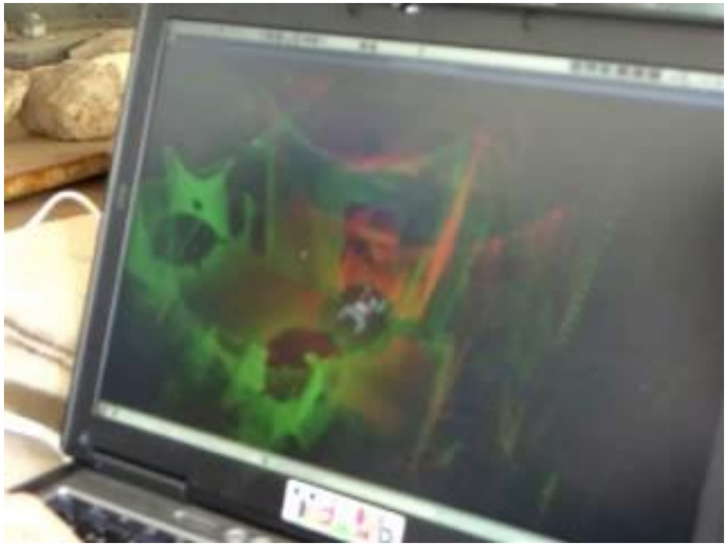
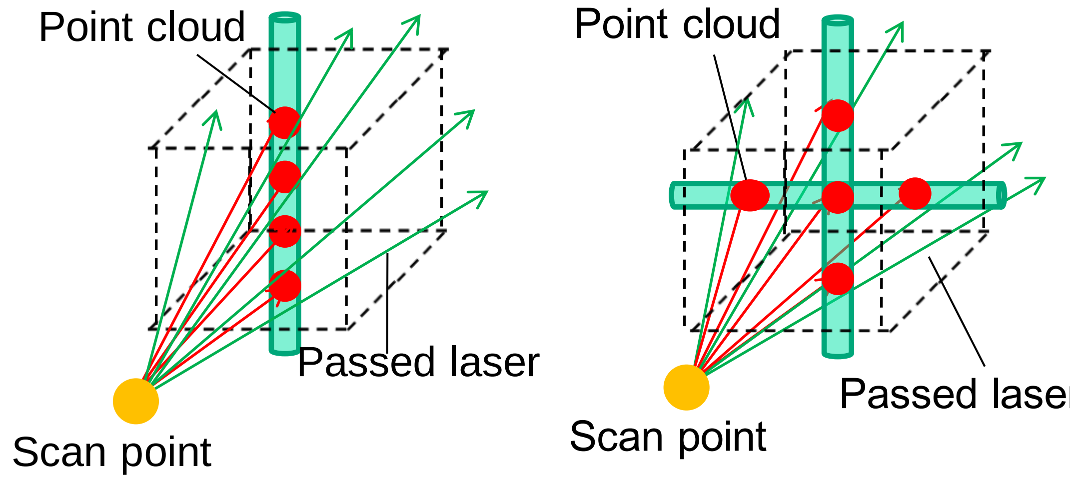
3D Interface @ Disaster City

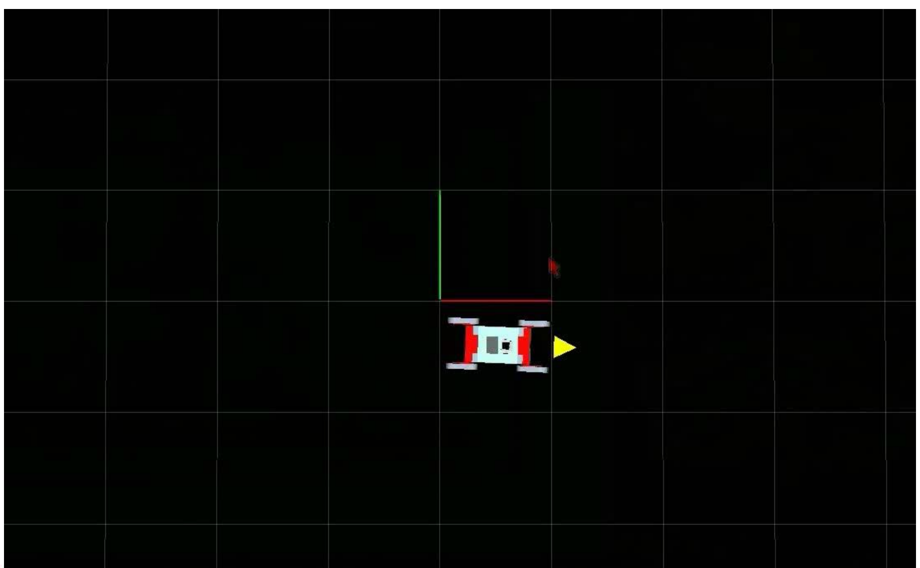


3D interface +
Rubble pile adaptation
in pancake crush structure

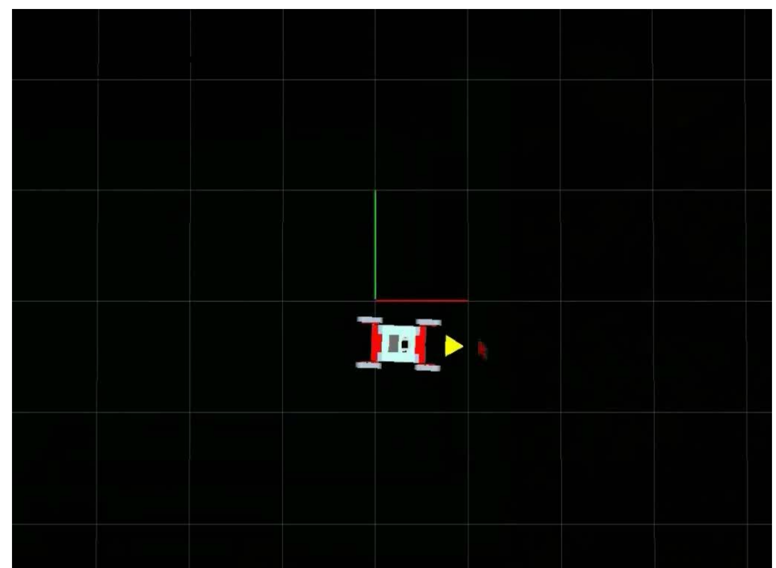
(2008.11.18-20)

Classification of 3-D Point Cloud



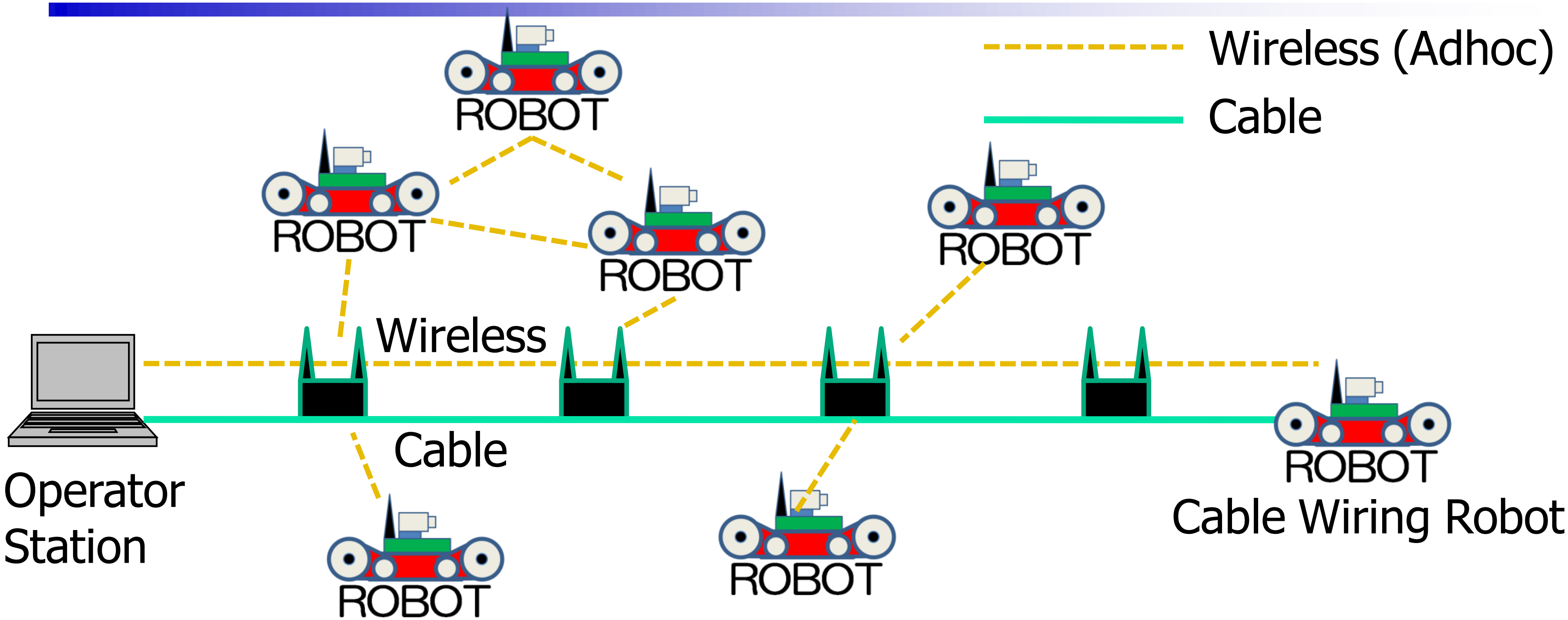


Point cloud



Classification result

Hybrid Adhoc Network of Wired+Wireless



- Capacity and Less Delay
  - Wireless --- Branch
  - Cable ------- Backbone
- Freedom of Robot Motion
  - Robots do not need relay data from the other robots
- Higher Reliability
  - Cable: robust against congestion
  - Redundancy: cable + wireless (backbone) --> robust against cut of cable

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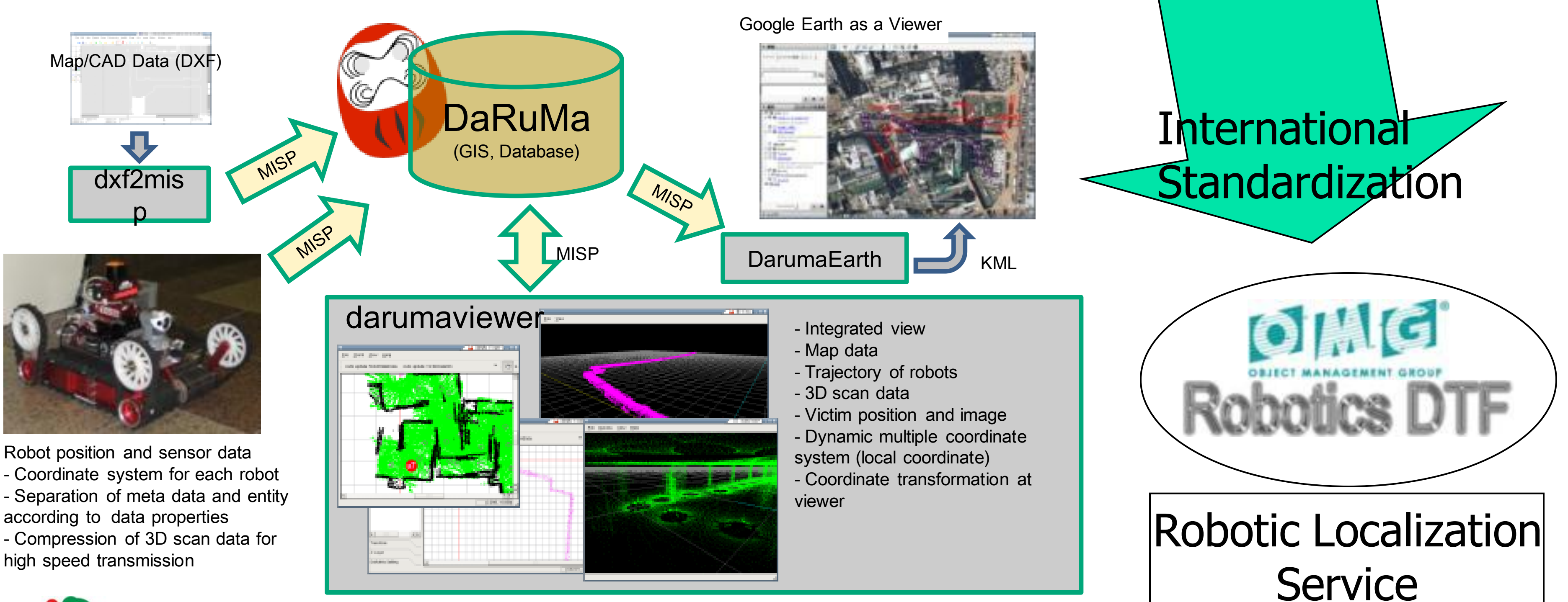
Integration of Data from Multiple Robots

- Technically Important Points
  - General data format, access method
  - Error of localization
  - Speed and high-tech func.

MISP + GML

Dynamic multiple coord. systems

Separation of sensor data and meta data



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Radiation Tolerance

- Knowledge base
  - Human workers may work up to a total dose 100 mSv/year.
  - Semiconductors are damaged by low radiation.
    - Mobile Pentium III 600 MHz can survive in total dose 23-93 Gy (Sv).
  - Materials are damaged by high radiation (MGy).
  - Bit change seldom occurs without charged particles.
    - Gamma ray is the major radiation in nuclear plant.
    - Gamma ray does not have charged particles.
  - Radiation at the entrance of RB is 10-100 mSv order.
  - In gamma ray, the two units are equal: Gy = Sv.
- Question
  - Can the consumer semiconductors and sensors work?
    - ATOM, CCD, LIDAR, battery, etc. of Quince work under a few Sv/h in the nuclear reactor buildings?
  - Is heavy shielding necessary?
    - Then, robots have no mobility.

Radiation Tolerance

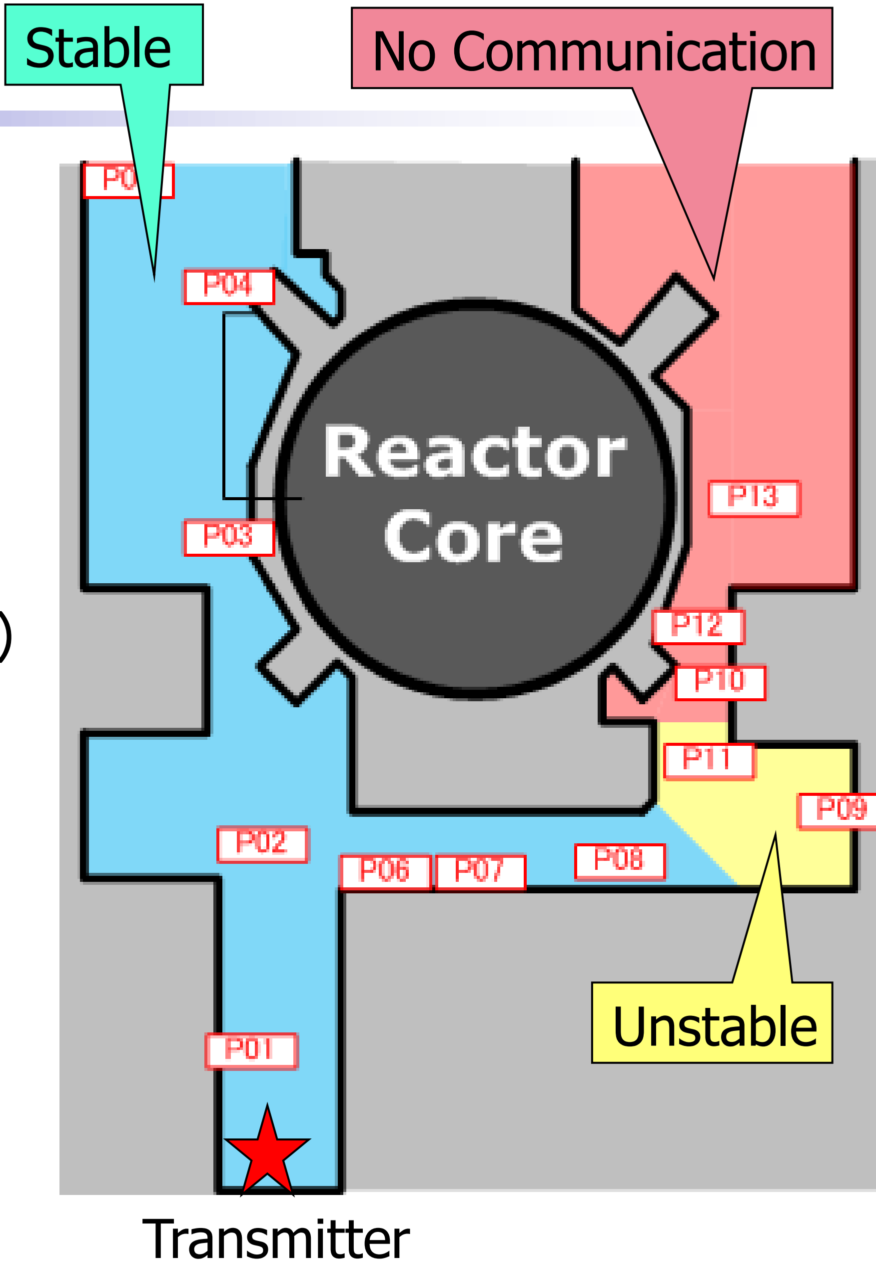
- Dose tolerance test at JAEA Takasaki Lab.
  - Cobalt 60 (20-40 Gy) for 5 hours
  - System functioning test by sensor test programs.
- Experimental Results: If 100mSv/h, and safety factor 0.1
  - LIDAR: 124 Gy (Sv) → 124 hrs = 5.2 days
  - CCD Camera: 169 Gy (Sv) → 169 hrs = 7.0 days
  - Others: over 200 Gy (Sv) → 200 hrs = 8.3 days
- Conclusion: Quince has enough dose tolerance.

Communication

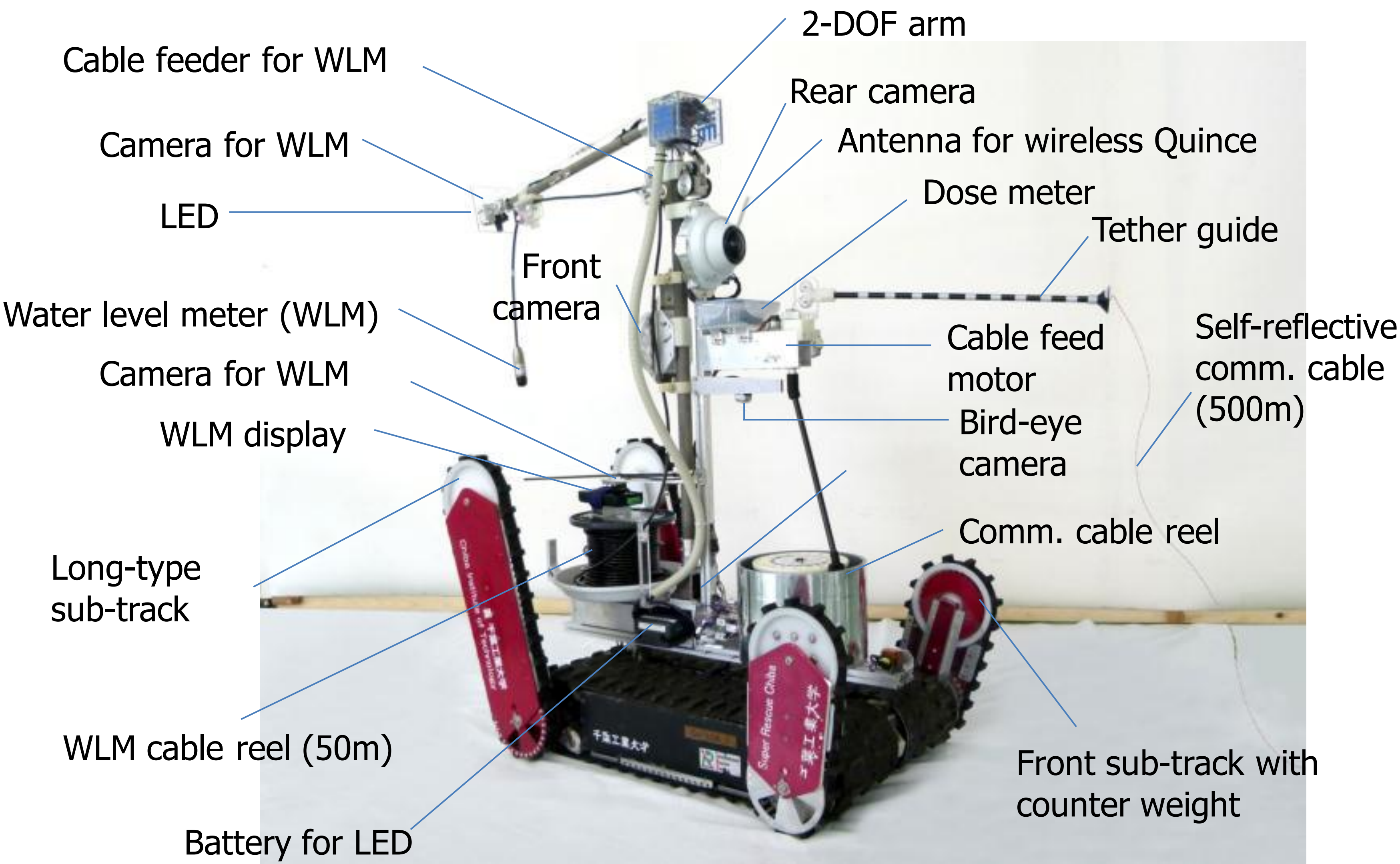
- Knowledge base
  - Wireless LAN (2.4 GHz) of Japanese regulation reaches only 50 m on line of sight.
  - Remote control from up to 400 m in distance is required, although the size of RB is 50 x 50 m.
    - Then, high power? How much? 100W?
  - Difficulty of wireless communication at narrow steps in firefighters' training towers surrounded by RC.
  - RB has perfect shield to prevent radiation.
  - Lower frequency can reach beyond obstacles.
    - Then, lower frequency?
- Question
  - Is wireless communication feasible in RB, or wired?
  - Does the change of power and frequency solve the issue?

Communication

- Communication test at Hamaoka Nuclear Power Plant at rest
  - RB1 & 2 have similar design as Fukushima-Daiichi.
  - Wireless LAN (2.4 GHz, 1W)
    -- higher power than the regulation (10mW/MHz)
  - Analog video tx (470 MHz, 1W)
    -- higher power
- Experimental Results
  - Wireless communication can be used only on line of sight.
  - Power and frequency did not change the results significantly.



Quince for Fukushima-Daiichi Nuclear Plant



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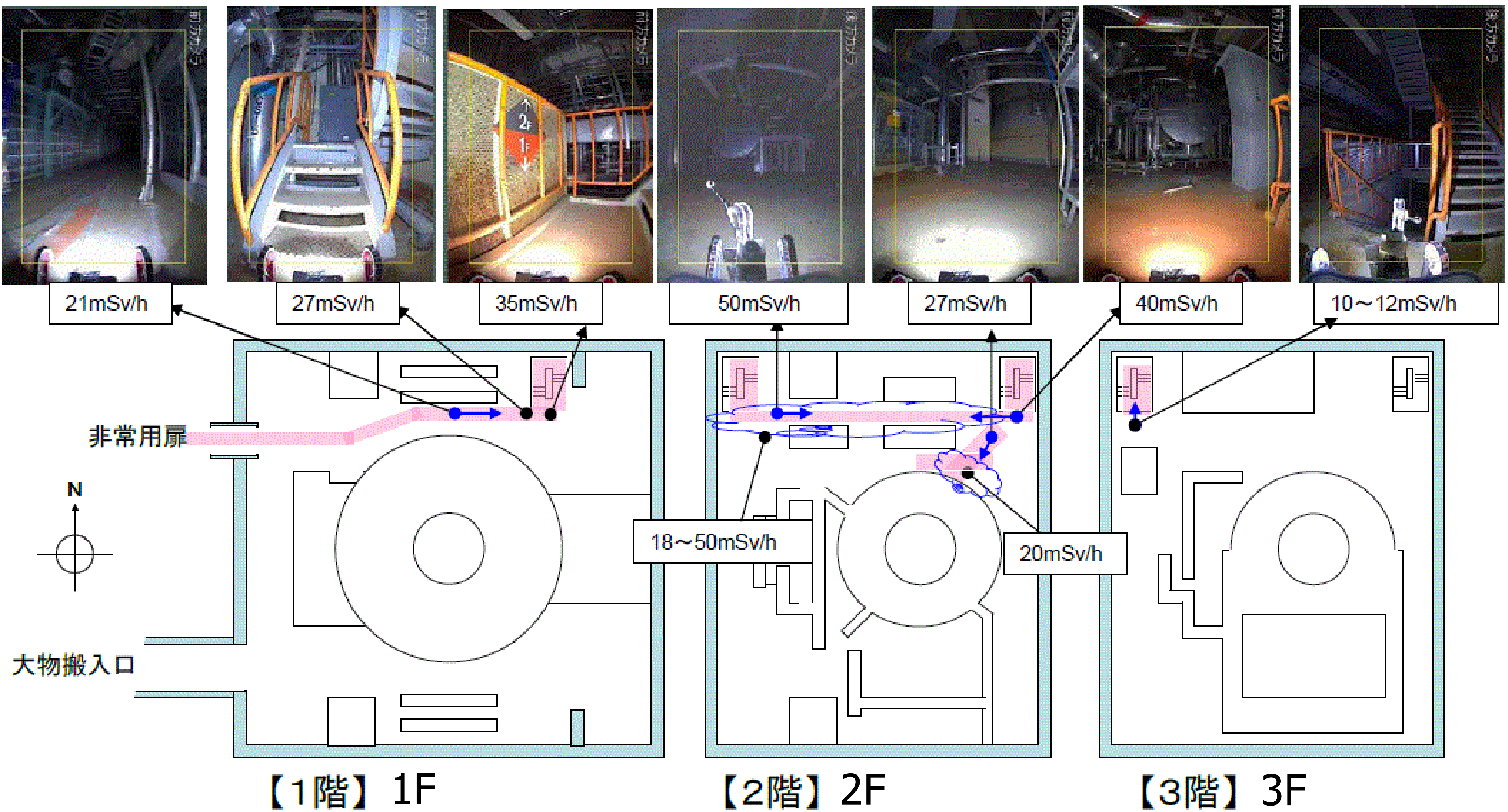
Quince in Fukushima-Daiichi
RB2 on July 8
(reported by TEPCO on July 11)

ロボットの移動経路

カメラの方向

平成23年７月11日
東京電力株式会社

水圧制御ユニット付近 | 1階北東階段前 | 1階→2階の途中 | 前方　原子炉補機冷却系熱交換器 | 前方　格納容器 | 2階北東階段前 | 3階北西階段前

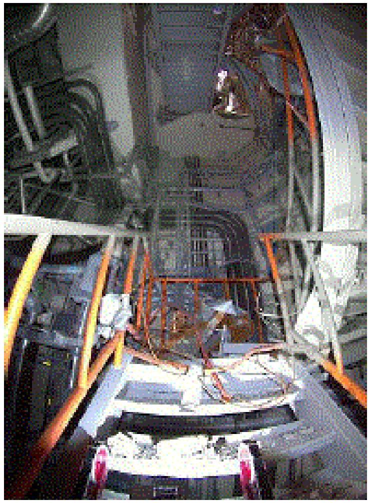


建屋配置はイメージ（縮尺や配置などは正確ではありません）

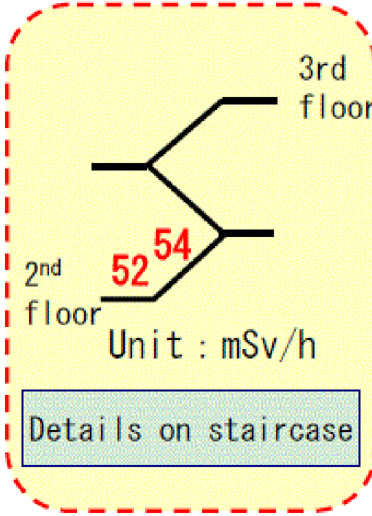
July 27, 2011

Tokyo Electric Power Company

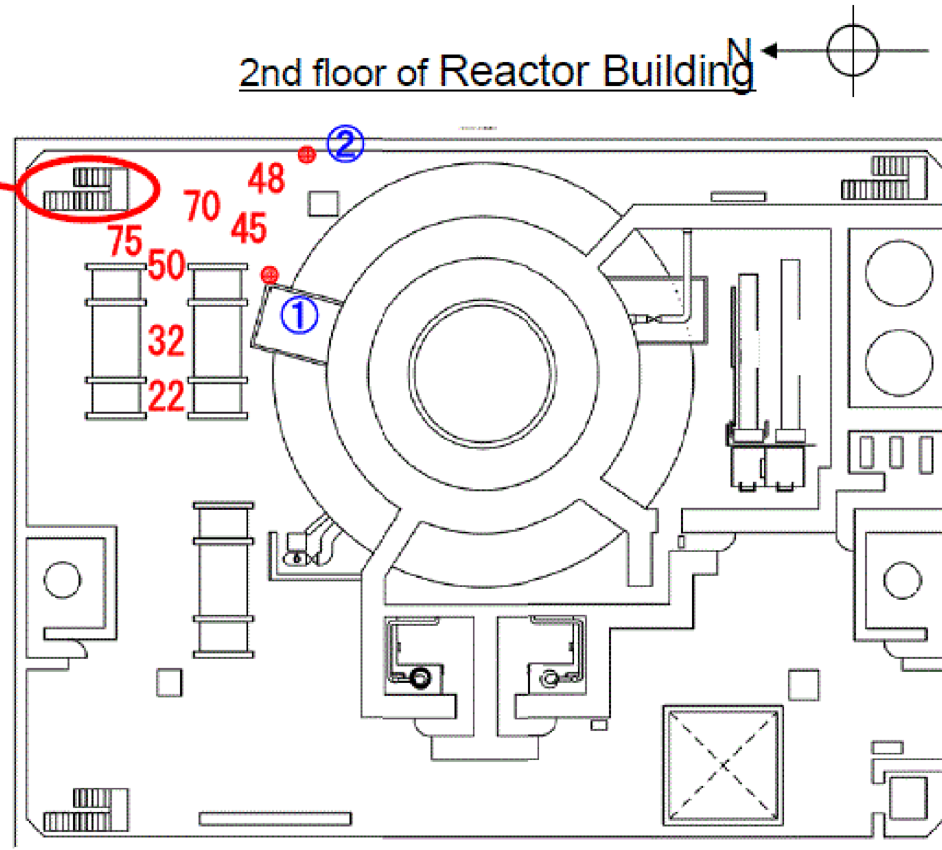
Fukushima Daiichi Nuclear Power Station Reactor Building of Unit3 Site Investigation by Quince



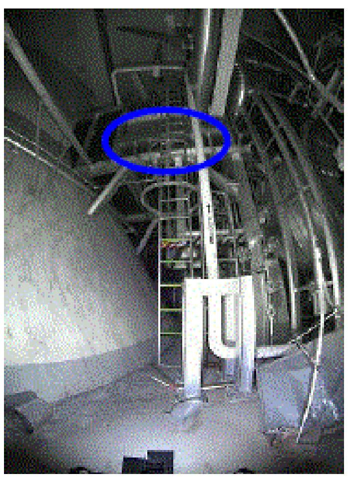
Staircase from 2nd floor to 3rd floor



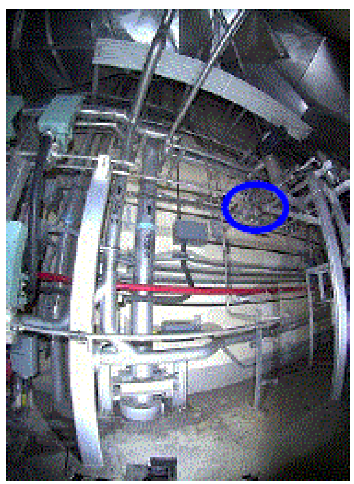
2nd floor of Reactor Building



※Image (there are no accuracy on reduction scale and layout)



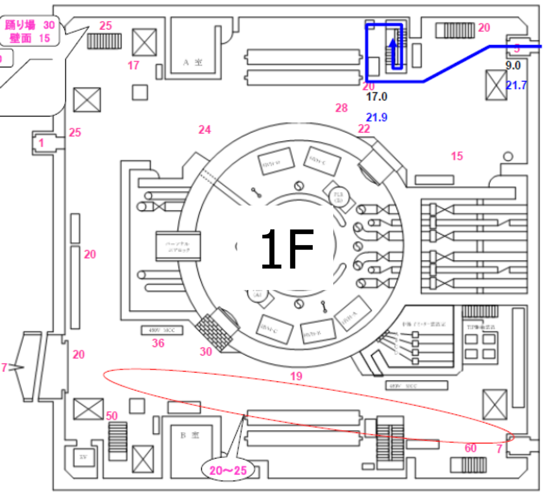
Grating at the valve of Core Spray System (point at ①)

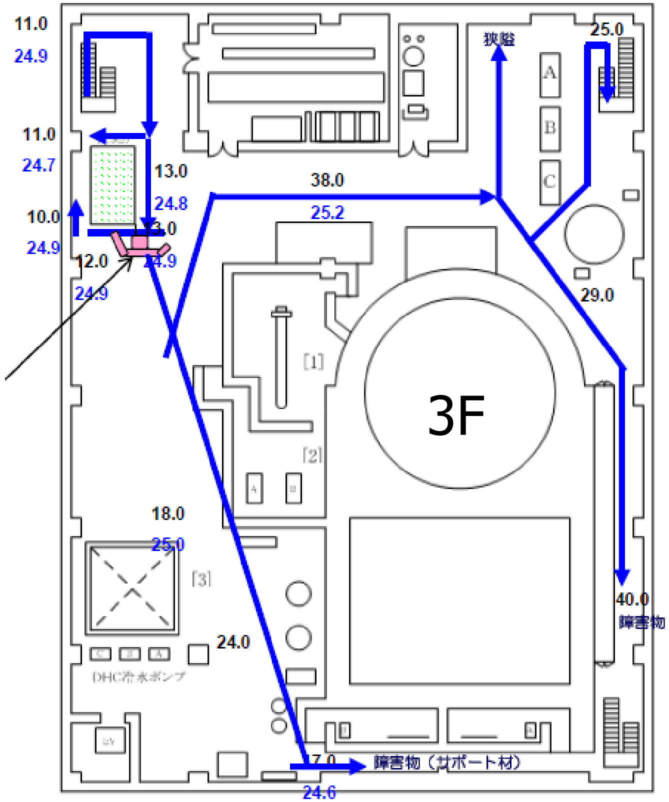


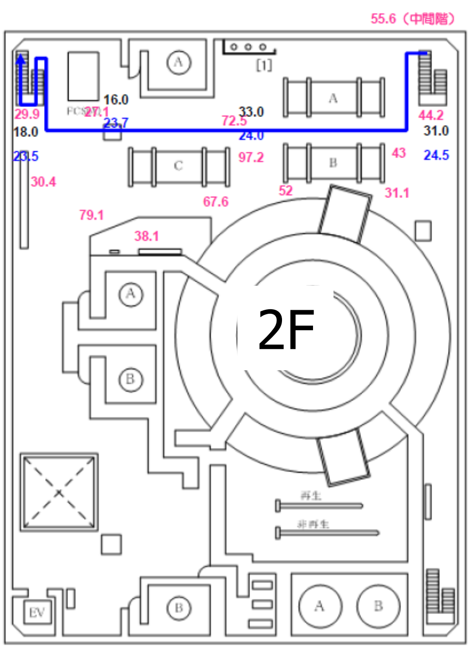
Valve of Water Supplement (Point at ②)

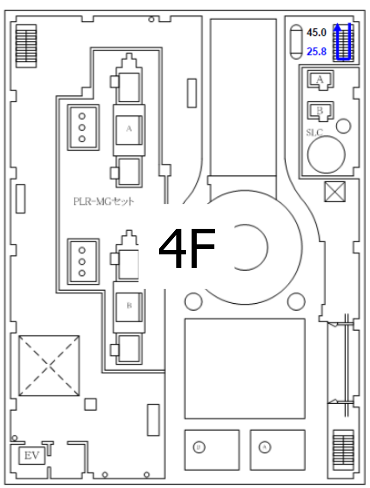
※All photos took by Quince

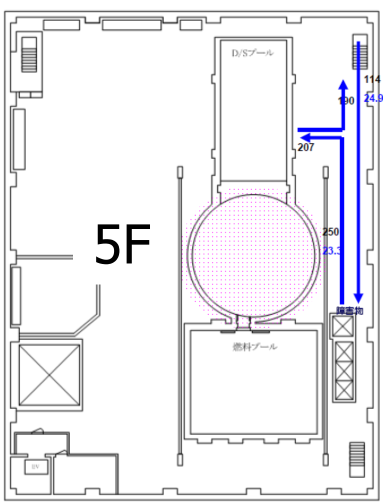
Quince in RB2 on Oct. 20 (by TEPCO)











What Were Accepted by Users

- High performance of mobility
  ← After they experience the difference.
- HD camera
  ← Easy to understand.
- Wired communication
  ← They thought it stable (but easy to be cut...)
- Transparent user interface
  ← They must avoid failure by misunderstandings.
- Training and exercise
  ← They checked the robot capability.
  They knew the issues to be solved.

What Were NOT Accepted by Users

- Autonomous motion
  ← The users cannot predict the robot behavior.
- 3D measurement
  ← The users think they know all the shapes
  (but exploded parts are...)
- 2 robots of wired and wireless
  ← Double operators are explosed to radiation.
- Wireless communication
  ← Not stable.

Does this (seems to) contribute to the solution?

Does this (seems to) obstruct the mission?

TEPCO's Lessons

- What is the response robot?
  - Myth: Severe accident never happens
- Guideline of robot use
  - Adopt the best matching solutions one by one
  - Avoid possible failure and obstruction by troubles
  - Exercise and simulation at Unit 5 beforehand
- Issues of robot functions
  - Manned work vs. robot work
  - Reliability
  - Wireless vs. wired
  - Radioactive environment
  - Adaptability to wide range of tasks

TEPCO's Lessons

- Issues of robot operations
  - Intuitive easy teleoperation
  - Quick setup and clearance
  - Logistics and light weight
  - Operator environment
- Issues of robot maintenance
  - Decontamination for reducing exposure
  - Maintainability on site

Our Lessons

- User-R&D communication and user education/training under real/realistic situations are essential.
  - Users did not know what helps them.
    (and still may not know fully)
  - Engineers and researchers did not know what users need.
    (and still may not know fully)
  - Users did not know what spoils the robot capabilities, and what unables it to complete the mission.
    (even though explained, before they experience)
  - Users operate the robots, and the researchers can never.
    (misunderstandings may cause accidents)

Users In the Loop

Robots as Useful Tools

- Robotic systems are becoming common useful tools in disaster response and recovery.
  ← EJ Earthquake was the historically first case where many robots were used.
- Robotic solutions
  - Accessibility to the disaster information
  - Information gathering at inaccessible places by human
- Fundamental problems to be solved
  - Accessibility to High Places and Narrow Confined Space
  - 70%: no problem, 30%: inaccessible
    → Robots cannot be used in real situations
  - Why inaccessible -- insufficient fundamental research

What research are needed to solve the 30%?

- Necessary advanced fundamental S&T
  - Mobility and positioning (high/narrow place, stability, ...)
  - Sensing and mapping (localization, imaging, victim recognition, inspection, robustness, big data, analysis, recognition, ...)
  - Light task execution (sampling, door opening, ...)
  - Communication (latency, capacity, relaying, ...)
  - Teleoperation/autonomy (controllability, situation awareness, automation, collaboration, reliability of tasks, ...)
  - Anti-explosion, durability, light weight, size, battery, logistics, ...

This problem is S&T for <u>Materialization of Synthetic Systems incl. Human under Severe Constraints</u>.

This is NOT a simple problem of mobility nor combinatorial issue for applications