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PROJECT STRATEGY FOR CLEAN-UP OF SEDIMENTARY RADIOACTIVE MATERIAL IN FUKUSHIMA BAY AREAS USING SNAKE-LIKE ROBOTICS

by

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The snake-like robot is used for clean-up project in Fukushima nuclear disaster site. The contaminated water at the Fukushima Daiichi nuclear power plants has been purified by the water treatment system, called Advanced Liquid Processing System, co-developed by Japanese and international technologies. The system is used to remove most remaining radioactive contaminants in water that had to be stored at the facility. In this paper, a snake-like robot, incorporated with Advanced Liquid Processing System is introduced for the severe accident in the nuclear power plants in which human cannot control the cleaning-up in the sea where the radioactive materials have been submerged and some resolved in the sea water. The effective strategy of the cleaning-up is analyzed from the environmental protection aspect with the snake's biomechanics and radioactive hazards.

Key words: snake-like robotics, nuclear power plant, Fukushima

INTRODUCTION

Following the Fukushima disaster the cleaning of the sedimentary radioactive material dissolved and submerged in the sea, has become a critical issue. The biomechanical robot is used for the clean-up project in Fukushima nuclear disaster site where the radioactive contaminated water has been poured into the Fukushima bay areas. The contaminated water at the Fukushima Daiichi nuclear power plants (NPP) has been controlled by the advanced water treatment system known as the Multinuclide Removal System (Advanced Liquid Processing System (ALPS)), developed by Japanese and international technologies [1], which was first installed at Fukushima Daiichi in October 2012, designed to remove the most remaining radioactive contaminants in water that had to be stored at the facility. This system has been used in the treatment of the site water produced from the underground water or rain. However, the contaminated sea water has not been treated by anything. Although the Prime Minister of Japan, Abe stated the contaminated water situation was under control [2], the operator of the crippled Fukushima Daiichi NPP said that radioactively contaminated rainwater was spilling outside the facility's port after the pumping, performed in order to prevent leakage, stopped working [3]. According to the plan, since the Fukushima disaster day of earthquake and tsunami, nearly 160 million gallons of contaminated water has accumulated in storage tanks on the site. About one half has been treated to remove most radioactive contaminants [4]. Other countries, like Oregon in the USA is testing for Cs-137 and Iodine-131 and proved the radiation came from Fukushima [4]. In November 2014, in the USA test results had shown that very low levels of Fukushima radiation had been detected about 100 miles off the coast of Eureka, California, and 400 miles off the coast of Newport, Oregon. The radiation at those low levels is not expected to harm humans or the environment [4]. Therefore it is reasonably needed to clean the sea water around the Fukushima bay areas including some contaminated coastal regions in Japan.

This paper shows the robotics for cleaning the sea water and submerged soils in the sea which have been contaminated by the radioactive material. The snake-like robot is expected to be useful to clean the radioactive contaminated sea water, because the body can move in the unregulated regions where the sludge, soil, metal, and more stuffs are intertwined. The movement mechanics are considered by the actions of the snake. The water treatment is a modified version of the conventional ALPS systems. Besides, the filtering of the soils is done by a centrifugal system in order to filter heavier soils. Figure 1 shows the simplified configuration of a snake-like robot for the sea water cleaning

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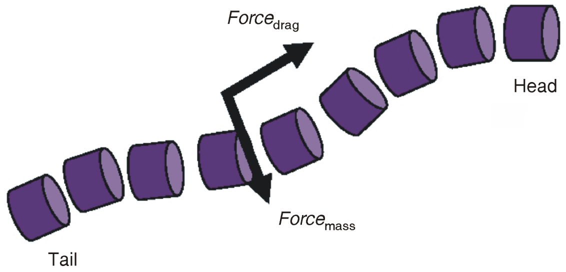

Figure 1. Simplified configuration of snake-like robot for sea water cleaning [6]

where the shapes of a number of ribs and spins are described by the simple cylindrical objects [5].

There are a number of studies on the radiation control of the nuclear disaster. Kozai *et al*. tested the radioactive fallout cesium (Cs-137) in the sewage sludge ashes (SSA) produced in Japan after the Fukushima Daiichi Nuclear Accident [6]. The sea water requires a highly advanced treatment of the cesium sludge where Fe-bearing phases, that were probably iron oxides, were mainly responsible for Cs-137 retention among the HCl-soluble sub-phases [6]. Method, results and some conclusions of the study are presented in the following sections.

METHOD

The water treatment

In the modeling of this study, the ALPS is modified for the clean-up project where the physical and chemical treatments are utilized. The biomechanical consideration of the robot is accompanied with the water treatment. Figure 2 shows the procedures of the ALPS where three stages are shown in the processing and the Iron includes the radioactive cesium [1]. This is called ALPS for the multinuclide Removal System and tab. 1 shows the target nuclides to be removed [1]. Figure 3 shows the configuration of clean-up in the Fukushima bay areas where the contaminated soils and sea water are sucked by the snake robot and then conveyed to the water treatment facility floated on the sea by the dock. The purified soil and water are dumped out to the sea. According to report [1], the system, the first of its type in the world on such a large scale (full capacity reaches up to 750 tons per day), has processed a total of approximately 230,000 tons of water in the trial operation until December 9, 2014. In the paper [7], the basic technologies/components of the APLS are:

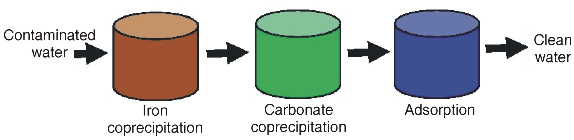

Figure 2. Procedures of advanced liquid processing system (ALPS) [1]

Table 1. Target nuclides to be removed [1]

Number	Nuclide	Number	Nuclide
1	Rb-86	32	Ba-140
2	Sr-89	33	Ce-141
3	Sr-90	34	Ce-144
4	Y-90	35	Pr-144
5	Y-91	36	Pr-144m
6	Nb-95	37	Pm-146
7	Tc-99	38	Pm-147
8	Ru-103m	39	Pm-148
9	Ru-106	40	Pm-148m
10	Rh-103m	41	Sm-151
11	Rh-106	42	En-152
12	Ag-110m	43	Eu-154
13	Cd-113m	44	Eu-155
14	Cd-115m	45	Gd-153
15	Sn-119m	46	Tb-160
16	Sn-123	47	Pu-238
17	Sn-126	48	Pu-239
18	Sb-124	49	Pu-240
19	Sb-125	50	Pu-241
20	Te-123m	51	Am-241
21	Te-125m	52	Am-242m
22	Te-127	53	Am-243
23	Te-127m	54	Cm-242
24	Te-129	55	Cm-243
25	Te-129m	56	Cm-244
26	I-129	57	Mn-54
27	Cs-134	58	Fe-59
28	Cs-135	59	Co-58
29	Cs-136	60	Co-60
30	Cs-137	61	Ni-63
31	Ba-137m	62	Zn-65

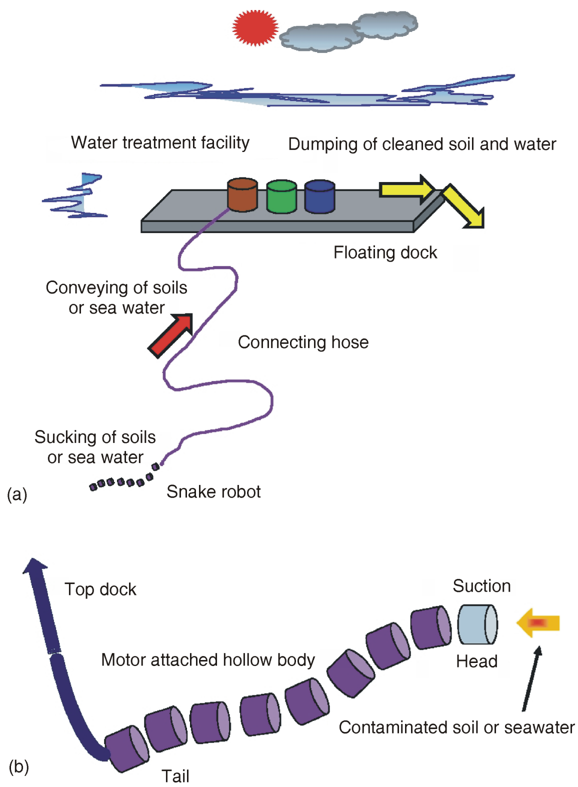

Figure 3. Configuration of clean-up in the Fukushima bay (a) landscape view and (b) detail of the robot

– mechanical, ultra, or hollow fiber filtration,
– flocculating, coagulation, and precipitating,
– organic ion exchange resin,
– various carbons,
– ion specific filtration/exchange materials, and
– PH adjustment.

There were several types of the NPP for the applications of this method including the cleaning of the contaminated water. In this study, the contaminated sea water and submerged soils are objects to be cleaned. For example, the radioactive water existed in the containment vessel at the Fukushima plant site where the water was poured up by fire trucks at the time of the explosion. The water removing from the plant equipment could be done by this robot attached system, because the hollow body will be used as the hose to suck the radioactive contaminated water from the floor of the reactor building or some facilities.

The mechanics of snake robot

The mechanics of the snake is applied for the robotic movements. In the real motion of the snake, the movement is done as the smooth continuous motions. Lv *et al*., design implies robot moving in water subject to the action of three forces, namely gravity, buoyancy, and hydrodynamic [5]. In the buoyancy force, $Force_{\mathrm{b}}$ is

$$Force_{\mathrm{b}} \quad \rho g V \qquad (1)$$

where ρ is the water density, g – the gravity, and V – the water volume [5]. Also, in the hydrodynamics, the mass force, $Force_{\mathrm{mass}}$, is

$$Force_{\mathrm{mass}} \quad \rho V M_{\mathrm{c}} A \qquad (2)$$

where M_{c} is the mass coefficient and A – the angular acceleration [5]. Then, the drag resistance, $Force_{\mathrm{drag}}$, is

$$Force_{\mathrm{drag}} \quad \frac{1}{2}\rho D_{\mathrm{c}} X_{\mathrm{a}} |V_{\mathrm{r}}| \qquad (3)$$

where D_{c} is the drag coefficient, X_{a} – the cross-sectional area, and V_{r} – the relative velocity of the robot [5]. Hence, for the stop of motion, the force should be zero

$$Force_{\mathrm{b}} \quad Force_{\mathrm{mass}} \quad Force_{\mathrm{drag}} \quad G \quad 0 \qquad (4)$$

where G is the gravity force [5]. If the robot is going forward

$$Force_{\mathrm{drag}} \quad Force_{\mathrm{b}} \quad Force_{\mathrm{mass}} \quad G \qquad (5)$$

If the robot is bending the body to a side direction

$$Force_{\mathrm{mass}} \quad Force_{\mathrm{b}} \quad Force_{\mathrm{drag}} \quad G \qquad (6)$$

According [8], the direction and bending angle of the snake robot are obtained

$$D_l \quad \tan^{1} \frac{y_l}{x_l} \qquad (7)$$

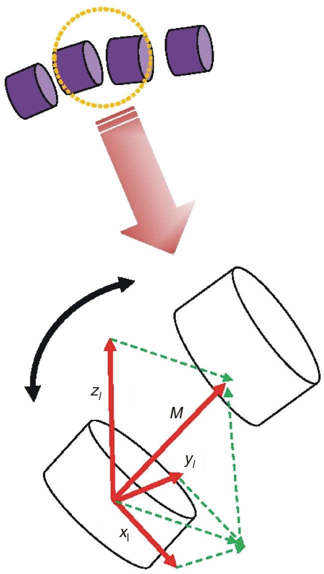

Figure 4. Co-ordinates of the robot movements [7]

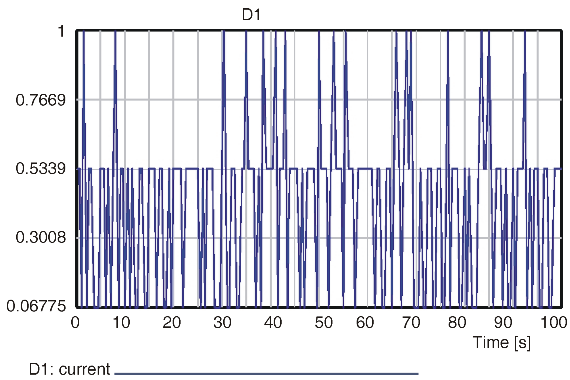

Figure 5. Directions of snake by random number generations

$$A_l \quad \pi \quad 2\tan^{1} \frac{z_l}{\sqrt{x_l^2 \quad y_l^2}} \qquad (8)$$

where the symbols are written in fig. 4. M is the vector summation of (x_l, y_l, z_l). So, one can control the robot by the relationship between $Force_{\mathrm{drag}}$ and $Force_{\mathrm{mass}}$. If

$$Force_{\mathrm{drag}} \quad Force_{\mathrm{mass}} \qquad (9)$$

the robot goes forward. If

$$Force_{\mathrm{mass}} \quad Force_{\mathrm{b}} \qquad (10)$$

the robot goes to side direction. Hence, the randomly changed motions in figs. 5 and 6 are manipulated by the $Force_{\mathrm{drag}}$ and $Force_{\mathrm{mass}}$.

The radiation control

The radioactive material in the water shows the decreased radioactivity by the exponential decay pattern where the most concerned material, Cs-137, has

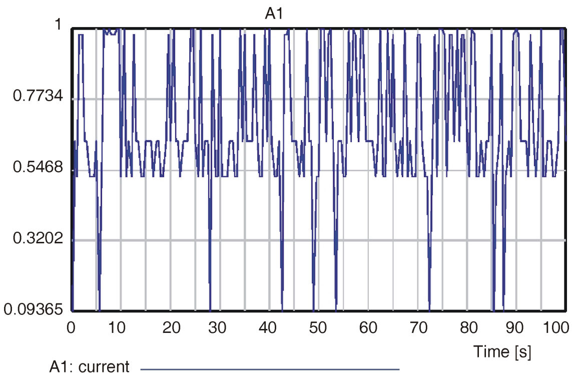

Figure 6. Angles of snake by random number generations

Table 2. Radioactivity [1]

Number	Contaminated water [Bqcm^{-3}]	ALPS treated water [Bqcm^{-3}]
Cs-137	$2.0\ 10^{1}$	$3.6\ 10^{-4}$

the radioactivity in tab. 2 for the Fukushima case. The activity of the sample using the decay equation is

$$A \quad A_0 \exp \quad \frac{\ln 2}{T_{1/2}} t \tag{11}$$

where, A_0 is the original activity of the sample, $T_{1/2}$ – the half-life of the sample, and t is the time. However, the perfect zero after ALPS treatment is not achieved, although the radioactivity decreases effectively. In the Fukushima site, the continuous radioactive material leaks to the environment. The completed removal of the radioactive material is nearly impossible, considering the waste treatment cost and the regional range to clean. During last several years, the contamination by this accident could be guessed in many areas of world. Fortunately, there is no report that this radiation contamination does affect the health of the human body significantly, until now. So, the key issue of the radiation control is to keep the environmental contamination at the level of safe human health.

RESULTS

There are some results regarding the snake-like robot used for the nuclear disaster cleaning. Figure 5 presents the graph for the directions of snake by random number generations and fig. 6 shows the graph for angles of snake by random number generations where the values are comparative values. This is based on the movements of the robot which are changed by the random number generated radioactive material waste distributions on the sea basement. The direction is normalized from 0.0 to 1.0. So, the forward direction is 1.0 and the backward direction is 0.0. The angle is normalized from 0 to 360 degrees. So, the 360 degree is 1.0 and 0 degree is 0.0 which have the same position. Each position is shown by a degree of change from 0 to 360 degrees, which is presented in fig. 7. So, the directions in fig. 5 and angles in fig. 6 are dimensionless values in y-axis of figures. In addition, the Vensim simulation code is used for Monte-Carlo simulation incorporated with random sampling quantifications [9]. In eq. (5), the drag force makes the forward direction. Otherwise, the mass force is the bending as 90 degree. So, the 1.0 means forward moves with drag force if is 0.5, the 90 degree bending. Two kinds of equations are interpreted by the moving direction. Figure 8 shows the Cs-137 radioactivity before and after ALPS treatments in which the comparisons between two treatments are also shown. The post radioactivity is

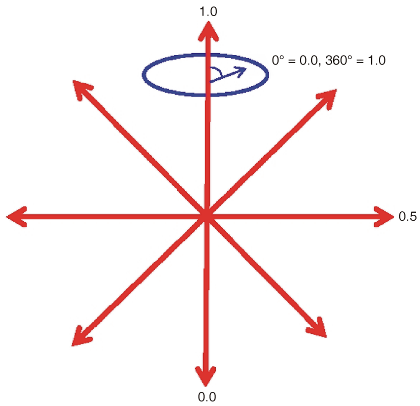

Figure 7. Directions and angles of robot movements

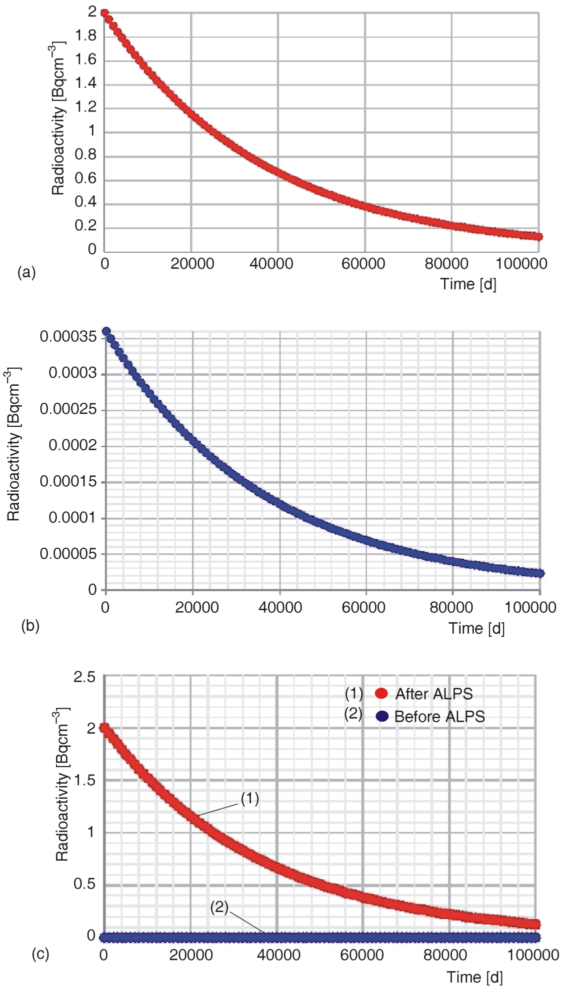

Figure 8. Radioactivity of Cs-137; (a) before APLS treatment, (b) after APLS treatment, and (c) comparisons between two treatments

much lower and not changed significantly which is in the exposure limit to humans.

CONCLUSIONS

The snake-like robot is studied for the severe accident in the NPP where human cannot control the cleaning up. Considering the environmental protection, the sea water treatment is very important. The neighbor nations could also be involved in this clean-up project. There are some important points of this study:

the snake-like robot is utilized for the cleaning-up of the sea,

the environmental protective work is done,

biomechanical study is done incorporated with the chemical treatment, and

the robot controls the post-nuclear accident.

The post-nuclear accident activities, especially the treatment of the Fukushima accident has provoked serious concerns both of the domestic and international communities. The clean-up tasks need much money which does not produce any economic benefit at first sight. However, the damage of the radioactive hazard is done in the scale of the worldwide spaces. The water as well as the air quality is very important to the fishing industry. Furthermore, the sea water streams move in all directions. There is no boundary of the sea water stream. Hence, the cleaning of the contaminated sea water is extremely important, especially for the sedimentary radioactive material.

The snake-like robot could be used in narrow places or remote region hard to reach which are less accessible to humans. Furthermore; the flexible and radioactive-resistance robot could be used to take over the jobs of humans in the hazard situation like the place of the post-nuclear accident. Otherwise the snake robot has the limitation of the speed. The four- or two-legged robots can move much faster than crawling snake robot.

For considering the real application, it is needed to find the exact distribution of the radioactive waste at the sea basement. Since the sea water shields the radioactivity of the sedimentary radioactive nuclides especially for the neutrons and heavy mass nuclides, the radiation detection in the sea is not easy to find as distributions are changed frequently by the sea water streams. So, it could be conceivable to construct a combined detection system with other types of the robotics. For example, the submarine can detect the radioactive material at the seabed and the robot flying over the sea could detect the radiation coming out of the sea. Therefore, the multiple organized surveillance systems could be constructed and then the information of the detections would be transferred to the central control room where the operator can manage the organizational strategy of the water treatment. The drone and submarine-like robotics should be developed in which newly designed systems are to be equipped in the projects.

From the political aspect, the international cooperation for the clean-up project could be performed. Since the seawater flows anywhere in the world following the seawater stream pattern, the multinational co-work is needed. The evaporated water from the contaminated area contains the radioactive material. This could fall down by the rainfall to the regions which are far from the nuclear disaster areas. The international monitoring could be done deploying radiation detectors by each nation. Furthermore, the weather satellite can detect the major radiation quality in the air as well as the sea. Highly sensitive radiation detector can measure the regional radiation distributions. Once the map of the radiation contamination is made, the cleaning of the area could be done by the snake-like robot in the sea. In the land, the humanoids could be utilized in the radioactive, contaminated areas. Currently, some workers at the Fukushima site keep the level of the radiation dose to human body low. If the robot is used, the humans can be free from the radiation damages in the post-nuclear accident treatments.

AUTHORS' CONTRIBUTIONS

Both authors were equally involved in making this article.

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СТРАТЕГИЈА ЧИШЋЕЊА СЕДИМЕНТНОГ РАДИОАКТИВНОГ МАТЕРИЈАЛА У ОБЛАСТИМА ЗАЛИВА ФУКУШИМЕ ПРИМЕНОМ ЗМИЈОЛИКИХ РОБОТА

Змијолики робот користи се у пројекту чишћења простора нуклеарне катастрофе у Фукушими. Контаминирана вода у Фукушима Даичи нуклеарним електранама пречишћена је унапређеним системом за течно процесирање воде који је заједнички развијен применом јапанске и међународне технологије. Систем се користи за уклањање највећег дела преостале радиактивности у контаминираној води која је складиштена унутар електране. У овом раду приказан је змијолики робот са унапређеним системом за течно процесирање, примењљив у озбиљним акцидентима у нуклеарним електранама када људи не могу да контролишу процес чишћења у мору у коме је радиоактивни материјал потопљен и делом разложен. Анализирана је ефективна стратегија чишћења са становишта заштите животне средине применом змијолике биомеханике и радиоактивног хазарда.

Кључне речи: змијолики робот, нуклеарна електрана, Фукушима