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 (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.
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 seawater 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 seawater 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 seawater in the trial operation until December 9, 2014. In the paper [7], the basic technologies/components of the APLS are:

<table>
<thead>
<tr>
<th>Number</th>
<th>Nuclide</th>
<th>Number</th>
<th>Nuclide</th>
</tr>
</thead>
<tbody>
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<td>Ba-140</td>
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<td>59</td>
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<td>61</td>
<td>Ni-63</td>
</tr>
<tr>
<td>31</td>
<td>Ba-137m</td>
<td>62</td>
<td>Zn-65</td>
</tr>
</tbody>
</table>

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

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

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, \( \text{Force}_{\text{b}} \) is

\[
\text{Force}_{\text{b}} = -\rho g V
\]

where \( \rho \) is the water density, \( g \) – the gravity, and \( V \) – the water volume [5]. Also, in the hydrodynamics, the mass force, \( \text{Force}_{\text{mass}} \), is

\[
\text{Force}_{\text{mass}} = -\rho VM_c A
\]

where \( M_c \) is the mass coefficient and \( A \) – the angular acceleration [5]. Then, the drag resistance, \( \text{Force}_{\text{drag}} \), is

\[
\text{Force}_{\text{drag}} = -\frac{1}{2} \rho D_c X_s |V_r|
\]

where \( D_c \) is the drag coefficient, \( X_s \) – 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

\[
\text{Force}_{\text{b}} + \text{Force}_{\text{mass}} + \text{Force}_{\text{drag}} + G = 0
\]

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

\[
\text{Force}_{\text{drag}} > \text{Force}_{\text{b}} + \text{Force}_{\text{mass}} + G
\]

If the robot is bending the body to a side direction

\[
\text{Force}_{\text{mass}} > \text{Force}_{\text{b}} + \text{Force}_{\text{drag}} + G
\]

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

\[
D_l = \tan^{-1}\left(\frac{y_l}{x_l}\right)
\]

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

\[ A = A_0 \exp \left( \frac{-\ln 2}{T_{1/2}} t \right) \]  

(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 6. Angles of snake by random number generations](image)

**Table 2. Radioactivity [1]**

<table>
<thead>
<tr>
<th>Number</th>
<th>Contaminated water [Bq/cm(^3)]</th>
<th>ALPS treated water [Bq/cm(^3)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cs-137</td>
<td>2.0 \times 10^1</td>
<td>3.6 \times 10^{-4}</td>
</tr>
</tbody>
</table>

![Figure 7. Directions and angles of robot movements](image)

![Figure 8. Radioactivity of Cs-137: (a) before APLS treatment, (b) after APLS treatment, and (c) comparisons between two treatments](image)
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 seawater 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 seawater streams move in all directions. There is no boundary of the seawater stream. Hence, the cleaning of the contaminated seawater 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 seawater 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 seawater 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 humanoid 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.

REFERENCES


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СТРАТЕГИЈА ЧИШЋЕЊА СЕДИМЕНТНОГ РАДИОАКТИВНОГ МАТЕРИЈАЛА У ОБЛАСТИМА ЗАЛИВА ФУКУШИМА 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 јапanske и међународне технологије. Систем се користи за уклањање највећег дела према радиоактивности у контаминиранијој води која је складиштена унутар електране. У овом раду приказан је змијолики робот са унапређеним системом за течно процесирање, применљив 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 роботи, нуклеарна електрирана, Фукушима