ANALYSIS OF HUMANOID ROBOTICS FOR NUCLEAR DISASTER MANAGEMENT INCORPORATED WITH BIOMECHANICS

by

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The humanoid is investigated for the mechanical and physical aspect in the nuclear disaster, especially for a severe accident, which includes the core melting. There are some mechanical studies of the leg and hand of the humanoid in which the human mimicking features are described. The management of the task is accomplished by the three regional preparations. The robot is made of the radiation-resistance substance. Therefore, it could work on the normal task of a human for the removal of the broken debris in a collapsed building. However, there is a limitation for the use in the reactor core building due to very high temperature of the nuclear fuel. The regional classification of the site is studied for the practical purposes. The post-accident analysis is accompanied with multidisciplinary research for the humanoid development in the nuclear industry.

Key words: robot, humanoid, nuclear power plant , disaster, safety

INTRODUCTION

The humanoid is investigated for disaster control in a nuclear accident like the Fukushima case. The radioactive material at the accident site is one of the important factors to find out the scale of the damage produced by the related explosion, heat, pressure, structure debris, and some more matters. The concentration of the radiation could reflect the degree of the accident, too. The relationship between the damage and the radiation concentration is studied by the humanoid involvement where the movement of the robot can give the information about the space that humans cannot approach due to the fatal radiation exposure from the nuclear fuel debris.

Since there are some differences between a robot and a humanoid, humanoid is used for the substitution of the human's behavior. There is a reason for using humanoid, to substitute a real person in a nuclear power plants (NPP) accident. In the NPP and those related buildings, the space is equipped suitable for the human's living, considering the height of the rooms and the paths. Hence, although there are many kinds of robot types, the humanoid could be a best machine for controlling the reactor and its related areas in the case of a NPP accident.

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Regarding the Fukushima nuclear disaster, the defense advanced research projects agency (DARPA) in the USA had organized a competition for a robot and its software team, in order to develop robots, which could work as human assistants in responding to any disaster like the Fukushima case [1]. There were ten kinds of obstacles to overcome in the contest in 2015, which are shown in tab. 1 [2]. In the competition, the most of the movements were done by leg and hand, where walking and finger manipulations were important skills. To master these functions were was a some significant tasks for the better functions functionalityby of a humanoid applicable for the a disaster. This is compared in the paper, because the contest was on the manipulation

Table 1. List of the ten kinds of obstacles in DARPA

Obstacle	Content
1	Drive a vehicle
2	Get out of the vehicle
3	Open a door and travel through the opening
4	Move debris or climb over it
5	Use a tool to cut a hole in a wall
6	Reach through an opening and open valve
7	Cross over a field of loose debris and pipes
8	Insert a cylindrical plug into a receptacle
9	Climb stairs with a rail on one side
10	Surprise manipulation task

of a humanoid in a nuclear disaster, which was a specific industrial accident.

In the previous human-like robot study, Zannatha *et al*. [3] studied a stroke rehabilitation system for the upper limbs which was developed as an interactive virtual environment based on a commercial 3-D vision system (a MicrosoftKinect), a humanoid robot (an Aldebaran's Nao), and devices producing ergonometric signals. Kanehiro *et al*. [4] worked for the reaching motion, planning and execution framework, tailored by human-operated humanoid robots, in some places like a NPP. In addition, Ricardez *et al*. [5] investigated a reactive strategy for human safety, which is called Asymmetric Velocity Moderation. Cho and Woo [6] studied the flying robot, the drone, in the nuclear disaster, for the cases of safety and security. Furthermore, the snake-like robot was applied for the Fukushima bay area cleaning [7]. Kong *et al.* [8] worked on the effluent monitoring of the environment, for radiation hazards. Cho and Woo [9] also worked on the nano-scale robot for the nuclear industry. The radioactive material concentrations and positions of the humanoid robot were investigated, in order to study behaviors in the disaster areas.

METHOD

The mechanics of movement

Following the necessity of the human-substitution robot in a nuclear disaster, the humanoid is to be developed in harsh conditions, where the extremely radioactive contaminated areas are presented, in nearly all the places at the plant site, with locally high temperature and pressure. Therefore, the robot should endure high temperature and pressure including very serious radiation exposure. Basically, the functions of humanoid need to include the movements such as the DARPA contest's tasks, with several detection systems for radiation, temperature, and pressure. However, in a real workplace, the force and moving abilities of the robot need to be much greater than those of a real human. First of all, the force of the hand as grapping, lifting, pulling, and pushing, and the force of the leg as walking, running, and kicking, should be sufficient to control the removal or arrangement of the broken building structures. Although, the robot could use any other heavy machinery, it is necessary to make them stronger. Figure 1 shows the normal feature of the NPP. In the accident like the Fukushima case, the buildings would be collapsed following the hydrogen explosion. Therefore, it is important for the humanoid to remove the debris in the highly radiation contaminated areas.

In order to study the moving mechanics of the robot, one should know the basic mechanics of a moving object. Figure 2 shows the six degrees of freedom for the robot movements [10]. The important things of the robot movements are the hand movement and walk-running behaviors. These are the basic features in the DARPA contest. Table 2 explains the relationship between the contest and the hand-leg mechanics.

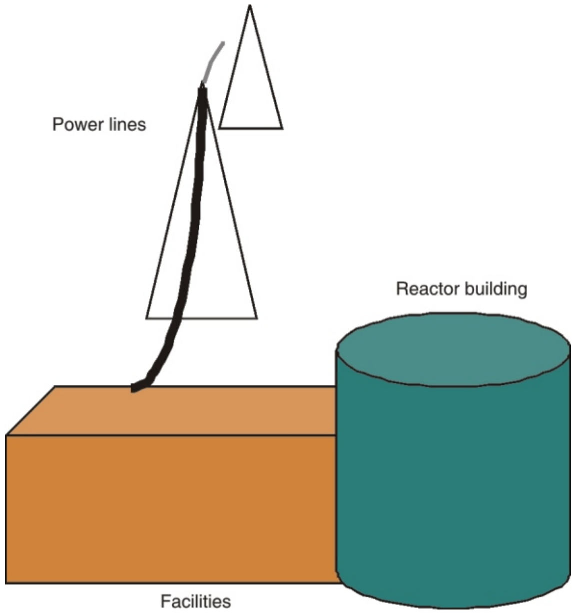

Figure 1. Simplified configuration of a NPP

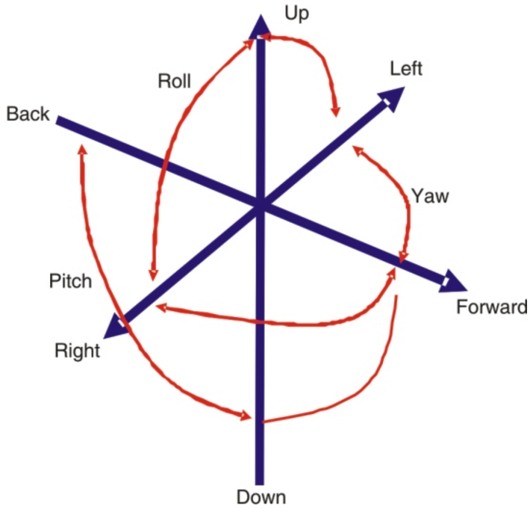

Figure 2. Six degrees of the freedom for the robot movement [10]

The mechanics of legs

There is the mechanics for walking in the humanoid. This mimics the walking of a human, which is shown in fig. 3. The 3-D divergent component of motion is described as follows [11]

$$s \quad x \quad c\dot{x} \tag{1}$$

where the transpose matrix forms as $s \ = [s_{\mathrm{x}}, s_{\mathrm{x}}, s_{\mathrm{x}}]^T$, $X = [x, y, z]^T$, and $\dot{X} \quad [\dot{x}, \dot{y}, \dot{z}]^T$. Then

Table 2. Classification of the hand-leg mechanics in DARPA contest

Obstacle	Used mechanics portion	Region
1	Hand	1
2	Leg	1
3	Hand and leg	2
4	Hand and leg	2.3
5	Hand	2
6	Leg	2
7	Leg	2.3
8	Hand	2
9	Leg	2.3
10	Leg	2

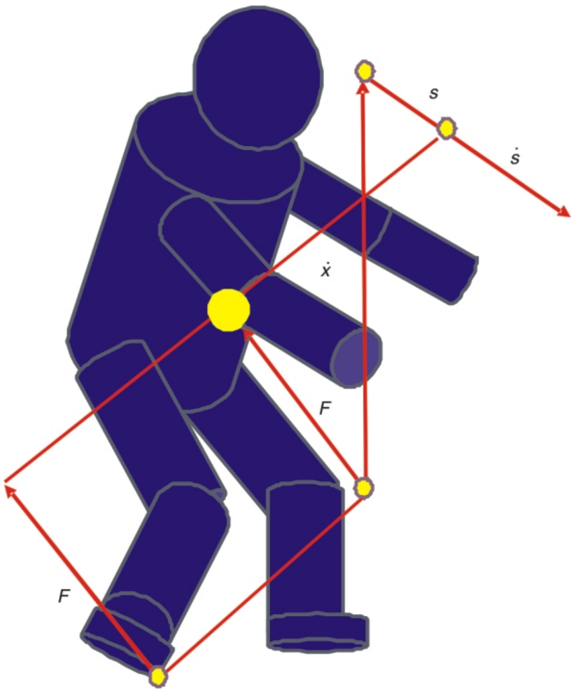

Figure 3. Simplified mechanics for walking of the humanoid

$$\dot{x} \quad \frac{1}{c}(x \quad s) \tag{2}$$

where $c > 0$. Also, the external force is as follows

$$F \quad \frac{m}{c^2}(x \quad t) \tag{3}$$

where m is mass and t is torque.

The mechanics of hands

Figure 4 shows the simplified finger mechanics of the humanoid's hand. Abdallah *et al.* [12] studied the mechanics of the hand of humanoids. Let us think the configurations as k, t, d, and f are the column matrices of joint angles, actuated joint torques, column matrices of tendon positions, and tensions, respectively [12]. So,

$$t = Rf \tag{4}$$

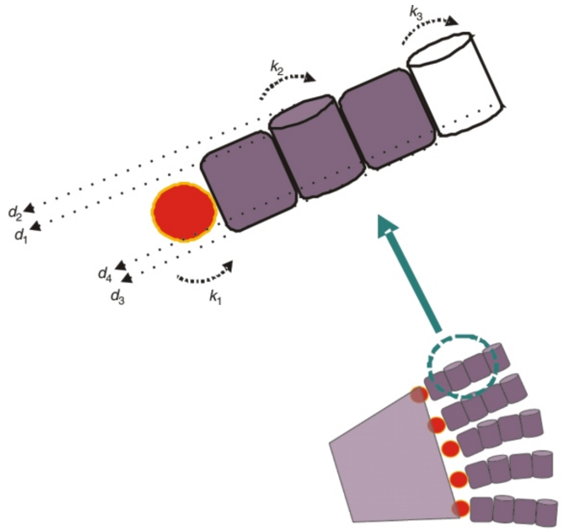

Figure 4. Simplified finger mechanics of the humanoid's hand

where R has the elements of the signed pulley radii in the tendon routing path [13]. In addition, by the principle of virtual work for the inextensible tendons [14],

$$\dot{d} \quad R^T \dot{k} \tag{5}$$

The calculation of radiation source position

This chapter explains the needs of the task of the humanoid where the NPP damage is related to the radiation leaks, because the exploded reactor is in contaminated, radioactive environmental. The radiation source is in the reactor core where the continuous radioactive material leaks and eventually is spread into the environment atmosphere, in the case of the core melting accident. Therefore, it is important to detect the damage degree in the core including its related facilities. The radiation quantity could be a clue for the damages of the core and nuclear fuel. The exact position and quantity of damaged reactor core are mathematically obtained by the following calculation. The leak radiation quantity is much more important compared to the leak position, because the position should be at the core surface. In fig. 5, there are three positions of the robotics where each position is shown as Position 1 (X_1, Y_1, Z_1), Position 2 (X_2, Y_2, Z_2), and Position 3 (X_3, Y_3, Z_3). Therefore, the position is the meeting point of the estimated source position circles, shown in fig. 6. In addition, the distance of the source is calculated from the direct line as it is in fig. 7. The distance between the position 3 and source is obtained by the exponential decay law [15]

$$N(x) \quad N_o e^{\lambda x} \tag{6}$$

So, x, $N(x)$, and λ are known and N_o is calculated by

$$N_o \quad N(x) e^{\lambda x} \tag{7}$$

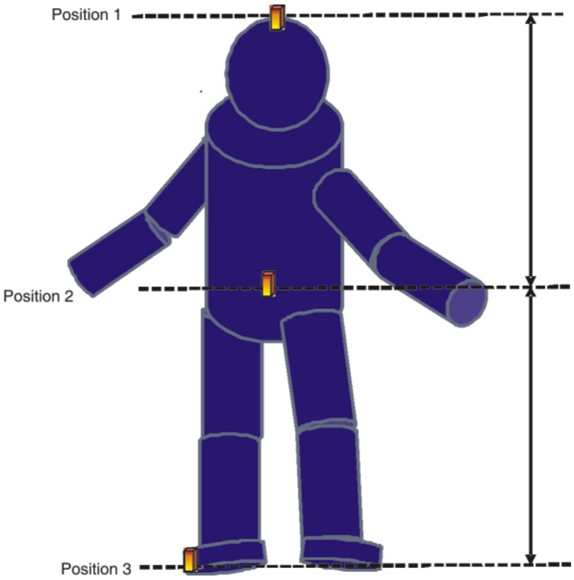

Figure 5. Configuration for the radiation detection

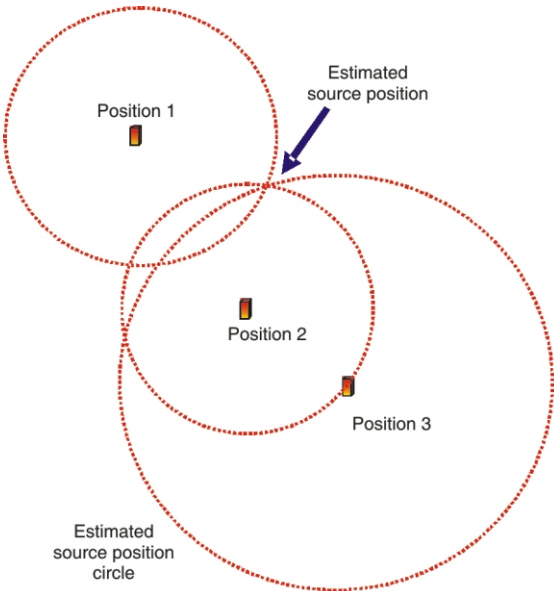

Figure 6. Finding the radiation position

Therefore, the radiation source position and quantity are obtained. However, the humanoid is away from the reactor core and the positions of the detector are very close outside of the core. In this case, the other robots could be used with multiple humanoids or drone, the flying robot, which is seen in fig. 8. For the three positions of robots, the source is not at zero point. Therefore, the source is located in the 3-D space. Using the decay equations, the radiation concentrations are shown as

$$N_1 \quad N_o(x)e^{\lambda|x_1 \quad x_o|} \tag{8}$$

$$N_2 \quad N_o(x)e^{\lambda|x_2 \quad x_o|} \tag{9}$$

$$N_3 \quad N_o(x)e^{\lambda|x_3 \quad x_o|} \tag{10}$$

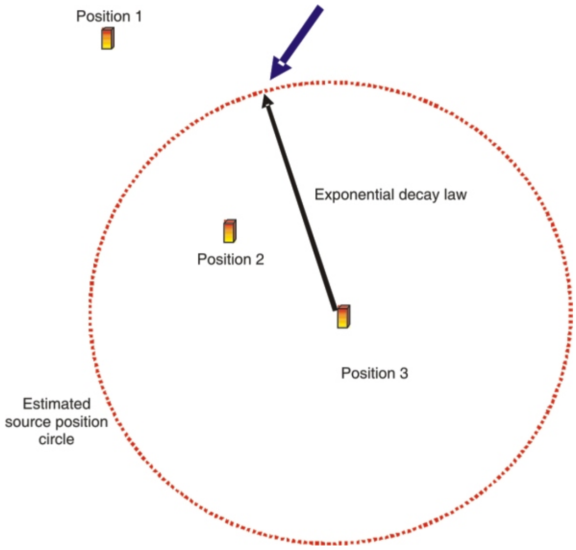

Figure 7. Finding the radiation position distance

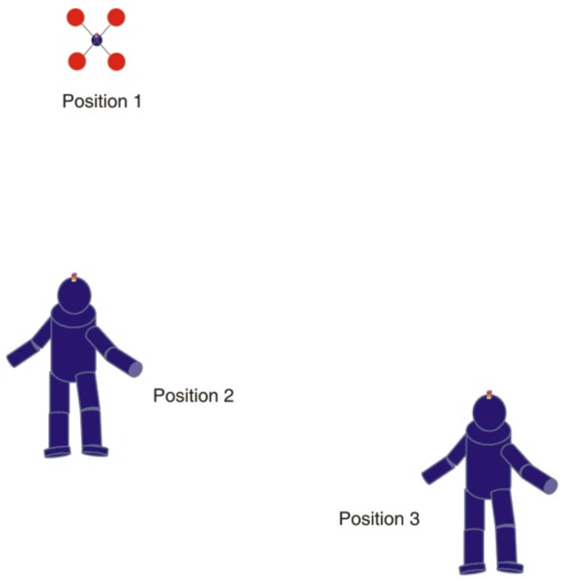

Figure 8. Combinations of humanoids and drones

Then,

$$N_o \quad N_1(x)e^{\lambda|x_1 \quad x_o|} \tag{11}$$

$$N_o \quad N_2(x)e^{\lambda|x_2 \quad x_o|} \tag{12}$$

$$N_o \quad N_3(x)e^{\lambda|x_3 \quad x_o|} \tag{13}$$

Therefore,

$$N_2(x)e^{\lambda|x_2 \quad x_o|} \quad N_1(x)e^{\lambda|x_1 \quad x_o|} \tag{14}$$

$$N_3(x)e^{\lambda|x_3 \quad x_o|} \quad N_1(x)e^{\lambda|x_1 \quad x_o|} \tag{15}$$

$$e^{\lambda|x_2 \quad x_o|} \quad \frac{N_1(x)}{N_2(x)}e^{\lambda|x_1 \quad x_o|} \tag{16}$$

Taking the log of eq. (16),

$$|x_2 \quad x_o| \quad \frac{1}{\lambda}\ln\frac{N_1(x)}{N_2(x)} \quad |x_1 \quad x_o| \tag{17}$$

then, source quantity N_o is obtained as follows,

$$N_o \quad N_2(x)e^{\lambda|x_2 \quad x_o|}$$

By the same way,

$$|x_3 \quad x_o| \quad \frac{1}{\lambda}\ln\frac{N_1(x)}{N_3(x)} \quad |x_1 \quad x_o| \tag{18}$$

$$N_o \quad N_3(x)e^{\lambda|x_3 \quad x_o|}$$

where x_o is obtained using the center of mass,

$$x_o \quad \frac{x_1 \quad x_2 \quad x_3}{3} \tag{19}$$

Similarly , the y_o and z_o are obtained. In the calculations, the wind speed and direction are not considered, because this space is in the small place as the only plant site. Although the space opens to the environment, the simple equation is used such as for the laboratory system. For example, if the ^{137}Cs is considered, with half-life of 30.17 years. So,

$$\lambda \quad \frac{\ln 2}{T_{1/2}} \quad \frac{\ln 2}{30.17\,\text{years}} \tag{20}$$

The management of the cleaning up

It is also needed to find the task object in differently contaminated areas, which is shown in fig. 9. That is, the external region, which is called Region 1, needs to be cleaned up by picking up the debris and vacuuming on the ground, because there is not much waste material. In the Region 2, it is necessary to use a machine like the crane to lift up some heavy stuff. Lastly, in the highly radioactive contaminated area, the humanoid should avoid the heat produced by the nuclear fuel. Several thousand degrees of temperature could melt the humanoid. In such cases, there is a need to use a machine operated with a remote control. There are regional classifications of the hand-leg mechanics in DARPA contest incorporated with the used mechanics portion in tab. 2.

RESULTS

The humanoid is investigated for mechanical and physical aspects in a nuclear disaster, especially for a severe accident accompanied with the core melting. There are mechanical studies of the leg and hand of the humanoid, in which the human mimicking is described. The management of the task is accomplished by the three regional preparations. Although the robot is made of radiation-resistant substance, it is a kind of machine that could be melted by a very high temperature. Figure 10 shows the humanoid action in Region 1, 2, and 3, where walking and standing are important behaviors together with the flying robot-drone. Especially, the Region 3 has highly contaminated exposure area. Hence, the humanoid needs the automatic machine like the crane. Therefore, the robot would be in a standing position. For the radiation calculations, fig. 11(a) shows the distribution of N_1. In fig. 11(b), the N_o is shown. It is assumed that the dose is normalized from 0.0 to 1.0. There are the radioactive material distributions as shown in figs. 11(c) X_o, 11(d) Y_o, and

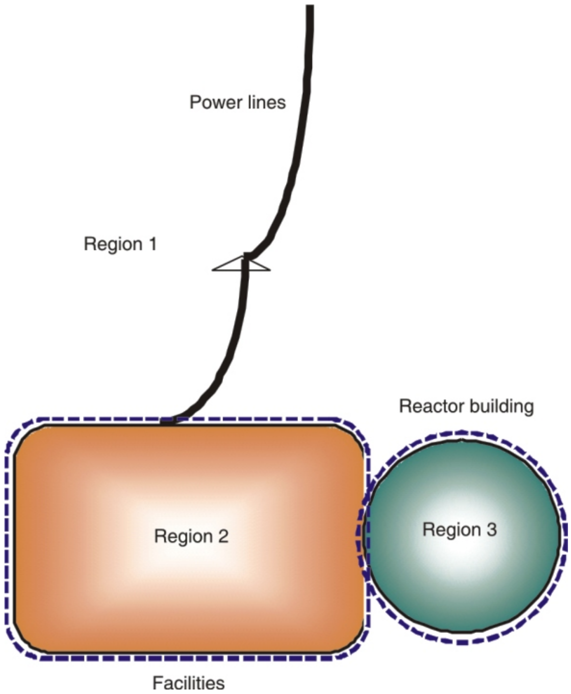

Figure 9. Classification of the three regions in the site

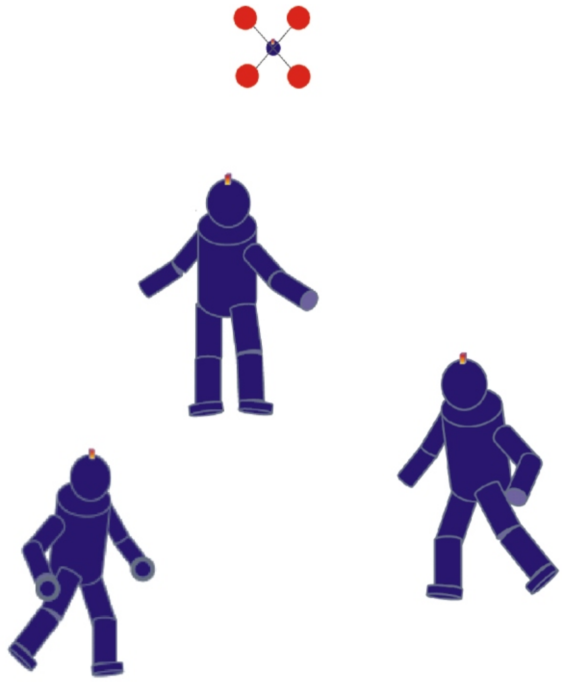

Figure 10. The humanoids for Region 1, 2, and 3

11(e) Z_o. The three positions of the robots in each place are obtained by the three kinds of random numbers. In the 27[th] minute, (X_o, Y_o, Z_o) is (0.3401, 0.5709, 05454) where the position is made by the arbitrary axis in this study. In the same way, the other positions can be calculated.

CONCLUSIONS

The humanoid is studied for the severe NPP accident situations where a human cannot control of the cleaning up. It should be able to accomplish normal tasks of a human for the removal of the debris in the collapsed building. There are some important points of this study as follows,

The humanoid robot is investigated for its role in the nuclear accident.

The effective and radiation-resistance resistant task could be accomplished.

Biology incorporated multidisciplinary technology is applied.

Post-nuclear accident is controlled by the robot.

This study shows the multidisciplinary strategy for the human-like robotics where the biomechanics, radiological technology, power plant, and post-accident analysis are combined in fig. 12. Until now, the nuclear accident analysis has been focused mostly on the before-accident analysis. The post-accident analysis could be done very effectively using the robotics technology, because it can work like a human in normal work places. The highly radioactive exposure in the severe accidents, like the Fukushima and Chernobyl cases, cannot give the humans a chance to work in the radiation contaminated areas. Therefore, the human workers should be substituted with the robots where the humanoid will work as much as a human in normal conditions, at work places.

The combinational work with drone is one of the best methods at the accident place. The applications of the robotics should be done by several kinds of robotics, including the flying and walking robotics. Hence, the adaptability to the accident place would be enhanced significantly. It is also needed to study the relationship between the electrical function and radiation damage. The high dose of radiation could effect the electrical assembly of the robot, even though the damage would not be high.

The other kinds of the robots could also be imagined – like the swimming robot. This could be used in the core where the coolants are fully or partially filled in the broken structures. Such a robot could send the information of the primary loop including the temperature and pressure. The information would be analyzed for estimation of the damage of the reactor and the external radiation rate. The animal mimicked robots could give good remedies in the severe accident of NPP. In the future, the general strategy for the

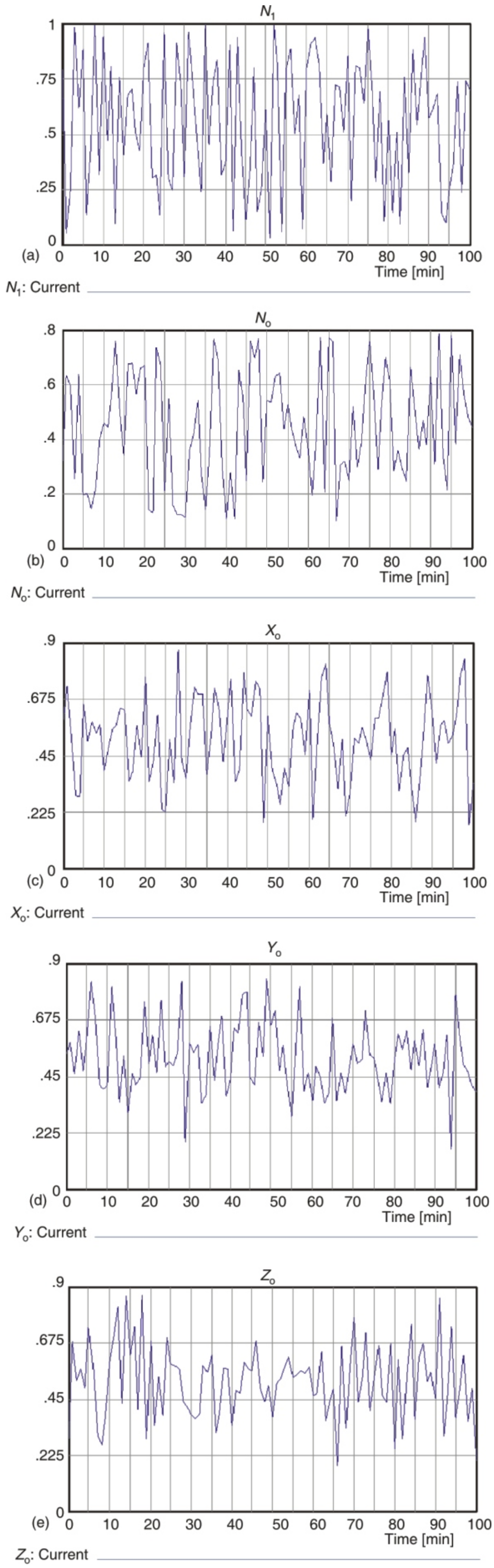

Figure 11. The distribution of (a) N_1, (b) N_o, (c) X_o, (d) Y_o, and (e) Z_o

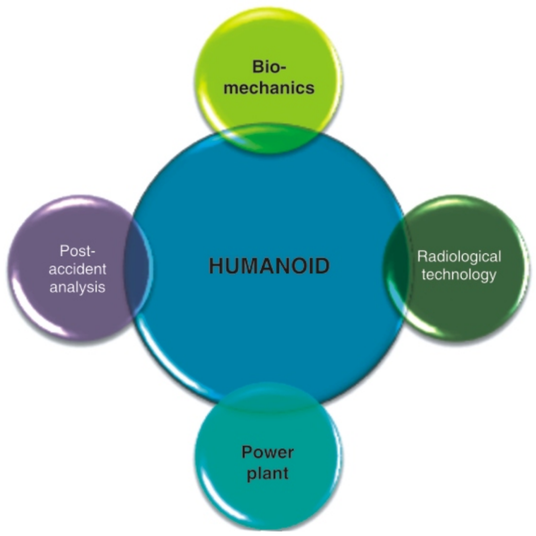

Figure 12. Multidisciplinary research for the humanoid development in the nuclear industry

post-accident could be accomplished by combinations of many kinds of robots with reference to this paper, where the humanoid and drone are suggested to be used in NPP accident.

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AUTHORS' CONTRIBUTIONS

K. B. Jang and T. H. Woo have prepared for this paper including manuscript, figures and tables.

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АНАЛИЗА ХУМАНОИДНОГ РОБОТА СА УГРАЂЕНОМ БИОМЕХАНИКОМ ЗА УПРАВЉАЊЕ У СЛУЧАЈУ НУКЛЕАРНЕ КАТАСТРОФЕ

Механичка и физичка својства хуманоидног робота истражена су у случају нуклеарне катастрофе, нарочито у тешком акциденту који укључује топљење језгра. Постоје студије о испитивању механичких карактеристика ноге и шаке хуманоида у којима су описане особине опонашања човека. Управљање задатком је извршено кроз припрему три регионалне области. Робот је израђен од материјала отпорног на зрачење, те би могао бити коришћен уместо уобичајеног рада човека при уклањању остатака урушене зграде. Међутим, постоји ограничење у употреби у згради са језгром реактора због веома високе температуре нуклеарног горива. Класификација области локације је проучавана из практичних разлога, а анализа након акцидента пропраћена је мултидисциплинарним истраживањем ради развоја хуманоида у нуклеарној индустрији.

Кључне речи: робот, хуманоид, катастрофа нуклеарне електране, сигурност