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Conceptual Design of Portable Filtered Air Suction Systems For Prevention of Released Radioactive Gas under Severe Accidents of NPP

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1. Introduction

After the Fukushima nuclear accident, which is one of the worst nuclear accidents, great concerns on the safety of nuclear power plants (NPP) have been increasing. It becomes evident that severe accidents may occur by unexpected disasters such as tsunami, heavy flood, or terror. Once radioactive material is released from NPP through severe accidents, there are no ways to prevent the released radioactive gas spreading in the air [1]. As a remedy for this problem, the idea on the portable filtered air suction system (PoFASS) for the prevention of released radioactive gas under severe accidents was proposed [3]-[4].

In this paper, the conceptual design of a PoFASS focusing on the number of robot fingers and robot arm rods are proposed. In order to design a flexible robot suction nozzle, mathematical models for the gaps which represent the lifted heights of extensible covers for given convex shapes of pipes and for the covered areas are developed. In addition, the system requirements for the design of the robot arms of PoFASS are proposed, which determine the accessible range of leakage points of released radioactive gas.

2. Portable Filtered Air Suction System (PoFASS)

2.1 Overview of PoFASS

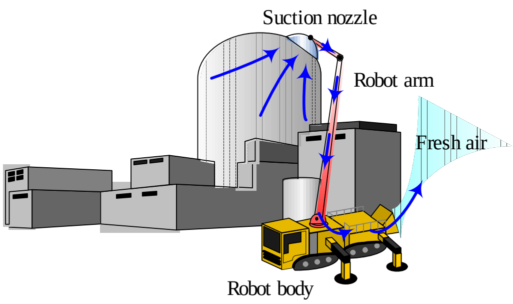
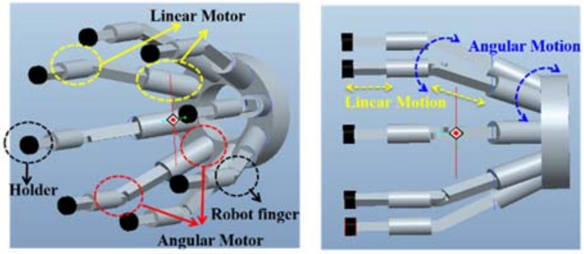


Fig. 1. Overview of a portable filtered air suction system [3].

In order to prevent the released radioactive gas from leakage points of NPP under nuclear accidents, the PoFASS composed of a suction nozzle part, a robot arm part, and a robot body part was proposed [3]-[4], as shown in Fig. 1. The suction nozzle part contains a flexible robot suction nozzle, which can be transformed in order to cover diverse broken shapes of leakage points. As shown in Fig. 2, a flexible robot suction nozzle consists of robot fingers, holders, extensible covers which make up for space between two robot fingers. The robot arm part composed of several joints and supports allows the suction nozzle for attaching to the leakage point. The robot body part is composed of sensors for radioactivity detection, a pump, a communication link, and a filter to purify the radioactive gas. The PoFASS could be a viable solution to mitigate the release of radioactive gas when the locations of leakage points are well recognized by radioactive detectors in NPP or UAV. For a multiple leakage points case, multiple PoFASS may be used.



(a) (b)

Fig. 2. Configuration of the flexible robot suction nozzle [3]. (a) Bird's view. (b) Side view.

2.2 System Requirements for PoFASS

The application of robots in NPP becomes essential since the Fukushima nuclear accident where the working conditions were substantially harsh and dangerous [5]; human access to the accident site was strictly restricted because of high radiation level and contamination. As a NPP robot potentially used for this purpose, the PoFASS should be designed considering the circumstances in order to mitigate the impact of severe nuclear accidents. Thus, the system requirements (SR) for a PoFASS are suggested in this paper as follows:

SR1. It shall be resistant to water, radiation, high pressure, and high temperature.
SR2. It shall be remotely controlled in real time.
SR3. It shall adaptably cover any broken shapes of leakage points around NPP.
SR4. It shall be able to attach to any locations of leakage points in NPP.

The resistance capability of SR1 is quite important for disastrous nuclear accidents. The remote control capability of SR2 is essential because human access to accident sites is strictly restricted. As in SR3 and SR4, which are mainly focused issues in the subsequent sections, it is crucial for a PoFASS to access to any locations outside of NPP. It should also be able to cover any broken shapes and leakage points for preventing released radioactive gas of high pressure and temperature from spreading in the air.

3. Conceptual Design of PoFASS

3.1 Flexible Robot Suction Nozzle Design, Focusing on the Minimum Number of Robot Fingers

In order to satisfy SR3, a flexible robot suction nozzle, which contains robot fingers and can be transformed to cover diverse broken shapes of the leakage point, was proposed, as shown in Fig. 2. The main design parameter of the suction nozzle is the number of robot fingers. The large number of robot fingers increases the complexity of control, and cost as well as the coverable capacity of the suction nozzle. Because of this trade-off, the design of the number of robot fingers should be needed. In order to determine the minimum number of robot fingers, feasibility analysis was conducted with classified broken shape cases of leakage point [3], which represent all possible broken shapes of leakage point in the NPP indicate all, as shown in Fig. 3. In cases where the leakage point occurs at the plane side of wall, and at the vertex of walls, three robot fingers are enough to isolate the leakage point from atmosphere, as shown in Figs. 3(a) and (c). Whereas, in case the corner of walls, the side of pipe, and the joint of pipe and wall, the number of robot fingers should be more than four, as shown in Figs. 3(b), (d), and (e). As a result, the minimum number of robot fingers to cover all the possible broken shape cases of leakage point is determined as four robot fingers.

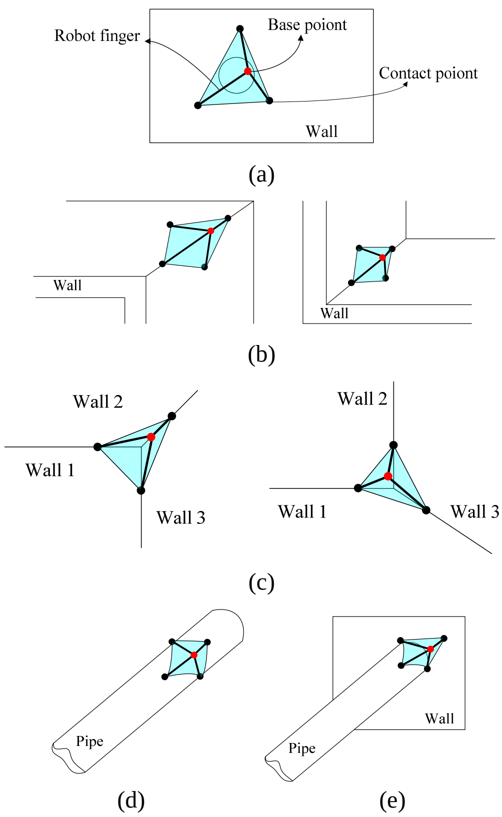


Fig. 3. Minimum number of robot fingers to cover the leakage point [3] in case of (a) side of wall, (b) corner of walls, (c) vertex of walls, (d) side of pipe, and (e) joint of pipe and wall fractures.

3.2 Flexible Robot Suction Nozzle Design w.r.t. the Gap

As a design issue of the flexible robot suction nozzle, the gap along the number of robot fingers should be considered, which represents the lifted height of extensible cover due to convex shape of the pipe, as shown in Fig. 4. In order to reduce the gap, the number of robot fingers should be increased because a side of the regular polygon, the covered area, becomes shorter, as shown in Fig. 5. With the projected length of robot finger on the surface l_f, and the trigonometric relationships among parameters, the perimeter of covered area l_p, the chord length of contact points d, and the cover angle θ can be determined as follows:

$$l_p = 2nl_f \sin\frac{\pi}{n}, \tag{1a}$$

$$d = 2l_f \sin\frac{\pi}{n}, \tag{1b}$$

$$\theta = \sin^{-1}\left(\frac{l_f}{r}\sin\frac{\pi}{n}\right), \tag{1c}$$

where n, *and* r represent the number of robot fingers, and pipe radius respectively. Then the gap h is determined as follows:

$$h = r[1-\cos\{\sin^{-1}(\frac{l_f}{r}\sin\frac{\pi}{n})\}]. \tag{2}$$

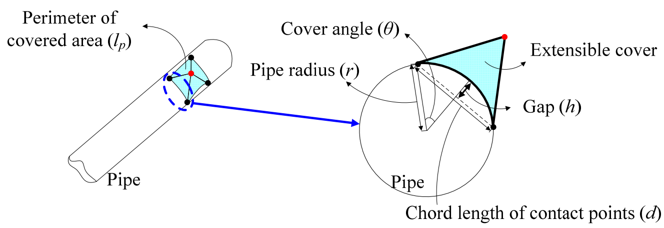


Fig. 4. Definition of the gap and parameters.

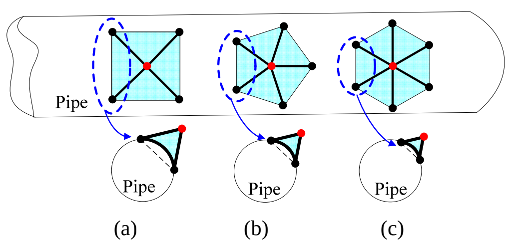


Fig. 5. Comparison of gaps along the number of robot fingers in case of (a) four robot fingers, (b) five robot fingers, and (c) six robot fingers.

As a design example of the flexible robot suction nozzle, the gap is plotted along the number of robot fingers from (2) for the cases where the location of leakage point is on the side of pipes whose diameter are 80 cm, 100 cm, and 120 cm, and the length of robot finger is chosen by 25 cm. The Fig. 6 shows the gap becomes reduced by increasing number of robot fingers, and the pipe radius. From this relationship, a design condition of the flexible robot suction nozzle can be obtained; in order to determine the number of robot fingers as four, which is the optimal number of robot fingers with consideration of control complexity and cost, the flexible robot suction nozzle should have tolerance for the deformation, 4 cm, as shown in Fig. 6. The deformation absorber which is put ahead of extensible cover, as shown in Fig. 7, can be a solution to satisfy the design condition of the flexible robot suction nozzle.

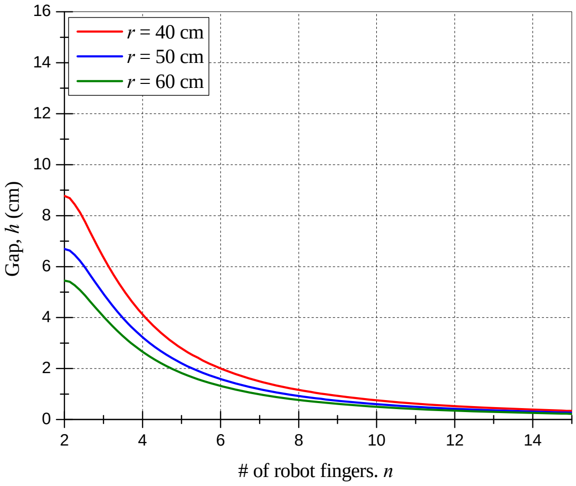


Fig. 6. The gap of the flexible robot suction nozzle along the number of robot fingers.

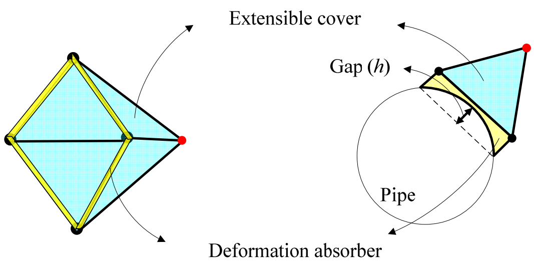


Fig. 7. Conceptual schematic of the deformation absorber.

3.3 Flexible Robot Suction Nozzle Analysis w.r.t. the Covered Area

As another design issue of the flexible robot suction nozzle, the covered area along the number of robot fingers is determined, which is the area among robot fingers projected on the structure, as shown in Fig. 8. By using the projected length as the length of robot fingers, the projected angle φ, the partial covered area S' are determined as follows:

$$\varphi = \frac{2\pi}{n}, \tag{3a}$$

$$S' = \frac{l_f^{\,2}}{2}\sin\varphi, \tag{3b}$$

where l_f represents the projected length of robot fingers. Then the cover area S is determined as a summation of the partial cover area as follows:

$$S = nS' = n\frac{l_f^{\,2}}{2}\sin\frac{2\pi}{n}. \tag{4}$$

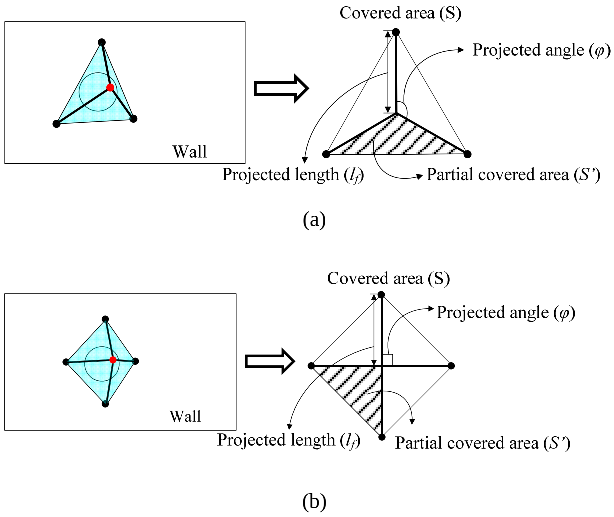


Fig. 8. Modeling of covered area in case of (a) three robot fingers and (b) four robot fingers.

As shown in Fig. 9, the covered area along the number of robot finger is plotted from (4) for the cases of the length of robot fingers are 25 cm, 30 cm, and 35 cm, respectively. The covered area increases and reaches to the constant value, which is the area of a circle having the length of robot fingers as a radius, with an increase of the number of robot fingers. Especially, when the number of robot finger is four and the projected length is 25 cm, the covered area is 1,250 cm^2, which is around 3 dB point of the maximum covered area. In addition, for the other cases where the projected lengths are 30 cm and 35 cm, and the number of robot fingers is four, the covered areas are around 3 dB point of the maximum covered area as well.

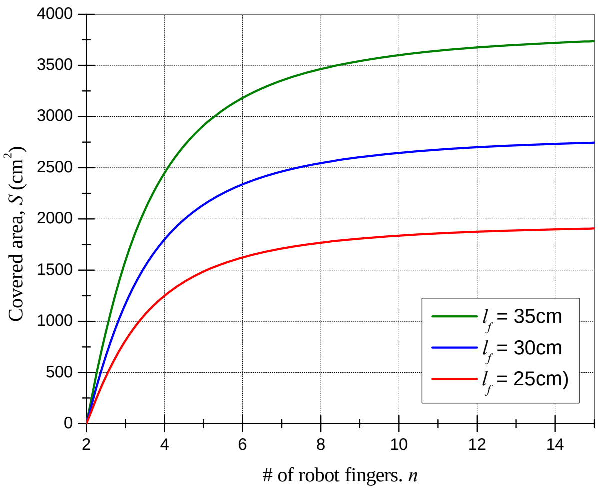


Fig. 9. Covered area of a PoFASS along the number of robot fingers.

3.4 Flexible Robot Arm Design, Focusing on the Minimum Number of Robot Arm Rods

In order to satisfy SR4, the PoFASS should be able to attach to any points in NPP, the robot arm should have enough degree of freedom. As shown in Fig. 10, the minimum number of robot arm rods can be determined with specific locations of the leakage points. When the robot arm has just one robot arm rod, the suction nozzle cannot be attached to the leakage point located on the top side of the building, as shown in Fig. 10(a). Even though the robot arm has two robot arm rods, the suction nozzle still cannot access to the leakage points which are located at the opposite side of the building, as shown in Fig. 10(b). It can be concluded that the number of robot arm joints should be at least three in order to attach to these points in NPP. Considering the massive size and complexity of NPP, e. g. the height of the APR 1400 is around 70m, the number of robot arm joints can be even larger than three because the maximum length of a robot arm rod for fabrication is practically limited.

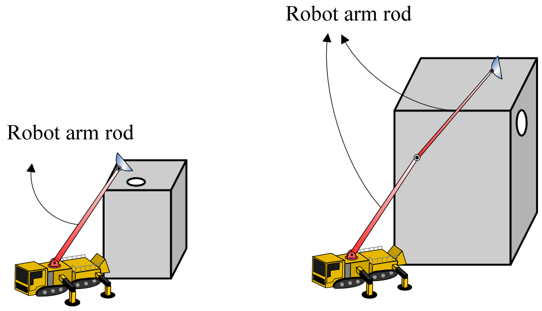


Fig. 10. Inaccessible leakage points of a PoFASS for the case of (a) one robot arm rod and (b) two robot arm rods.

When the leakage point is located in the range of the first robot arm rod, the suction nozzle cannot attach to the leakage point, as shown in Fig. 11. This range is defined as inaccessible zone. In order to mitigate this problem, the multi-stage rod composed of several stages to change the length of the rod can be used for the robot arm, as shown in Fig. 12(b).

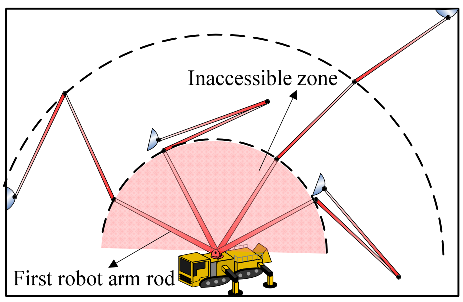


Fig. 11. Range of inaccessible zone of a PoFASS.

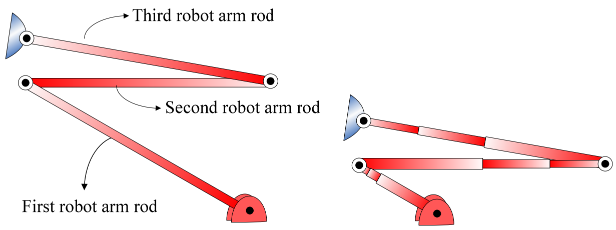


Fig. 12. Conceptual schematic for three robot arm rods (a) with a single stage and (b) with multi-stage.

4. Conclusions

In this paper, the conceptual designs of the flexible robot suction nozzle and robot arm have been conducted. As a result, the minimum number of robot fingers and robot arm rods are defined to be four and three, respectively. Moreover, the deformation absorber and multi-stage rod considering the tolerance of gap and inaccessible zone are also designed.

For further works, extensible cover designs on the flexible robot suction nozzle and the application of the PoFASS to the inside of NPP should be studied because the radioactive gas may be released from connection pipes between the containment building and auxiliary buildings.

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