Robotics for Nuclear Power Plants – Challenges and Future Perspectives

Jamshed Iqbal, Ahmad Mahmood Tahir, Raza ul Islam and Riaz-un-Nabi

***Abstract*—Use of robotics and computerized tools in Nuclear Power Plants (NPPs) has been identified as a highly recommended practice by IAEA. The key rationale of robotics application has always been to avoid human exposure to hazardous environments and tasks ranging from scrutiny and general maintenance to decontamination and post accidental activities. To execute these activities, robots need to incorporate artificial intelligence, improved sensors capability, enhanced data fusion and compliant human like leg and hand structures for efficient motions. Next generation robotic systems in NPPs are expected to work in full autonomous mode in contrast to the current semi-autonomous scenarios. Far future systems could deploy humanoid robots as well. This paper presents state-of-the-art of robotics developed for NPPs, associated challenges and finally comments on future directions.**

***Index Terms*—Robotics, Nuclear power plants, Mobile robots, Hazardous environment, Tele-operations**

I. INTRODUCTION

TECHNOLOGICAL advancement in robotics has ever increasing need and contribution in the safe and secure Nuclear Power Plants (NPPs). This increasing trend is not only associated with the revolution in robotics, automation and nuclear technology but is primarily because of the escalating concern over the human and environmental safety. Special attention has been drawn towards safety generally because of some major catastrophes in the nuclear industry; 'The Three Mile Island (TMI) accident' in 1979, 'Chernobyl tragedy' in 1986, and the most recent NPP misfortune at Fukushima in 2011. Such happenings, even in the presence of high-tech control systems and mechanization, demand for even better state of the art robotics technology and its reliable operational strength. Robots offer potential assistance in the routine functions of a NPP as well as to face the delicate and complicated situations involving mobility, tele-operations and radiation hardening.

According to International Atomic Energy Agency (IAEA), 435 Nuclear Power Plants are operational most of which are situated in 30 countries around the world. 65 more are under construction. In 2009, approximately 13.4% of the overall electricity was generated by the NPPs. Figure 1 shows world electricity production from nuclear sources as a percentage of total.

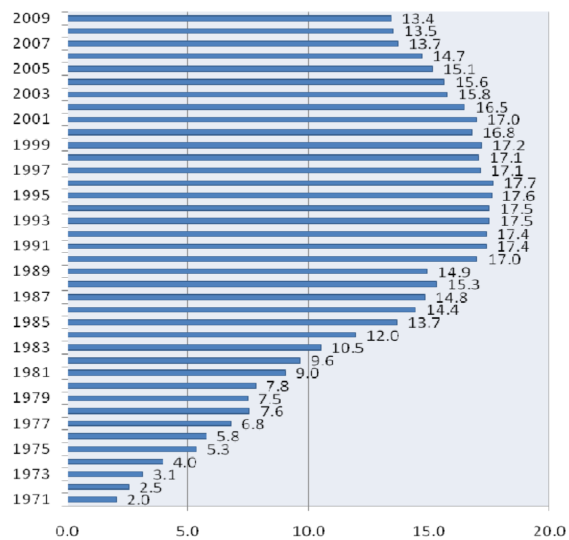

Fig. 1. World electricity production
(Source: World Bank Metadata)

IAEA strongly favors the use of robots in NPPs [1]. IAEA has put in regular efforts to improve the NPP operations' safety convincing all stake holders to develop state of the art control and instrumentation systems, robotic structures and intelligence techniques. One such attempt is proposition of the noise analysis technique [2] to increase the plants' safety with an ability of early stage detection of damages to the system. To deal with the day to day operations and emergency situations, simulators and computer modeling techniques are strongly recommended by the IAEA. The agency has also compelled the need to develop and apply better Human Machine Interfaces (HMI) to avoid the accidents based on the errors of human perception.

The key rationale of robotic applications has always been to avoid human exposure to hazardous environments and tasks ranging from scrutiny and general maintenance to decontamination and post accidental activities. The environments of NPPs certainly offer high temperature, humidity and radiation areas thus making human approach extremely limited. Nuclear industry utilizes robots as a mean of tele-operated machines to handle high risk movements in contaminated zones. Robots are used for mobile monitoring

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and surveillance to avoid the need of human inspection mainly to measure radiation level and temperature, producing contamination maps of a nuclear facility and to telecast local images. This technology helps in the inspection of reactor assemblies, pressure vessels, pipelines and assists in examination. Cleaning up floors, generators and storage tanks are some other important tasks performed by the robots in such a hazardous environment. Furthermore, deployment of robots in NPPs can eliminate the need to shut down the plant by providing on-line maintenance facility. NPPs also benefit from other universal advantages of robots including working with precision without any interruption during outage.

This paper first introduces an overview of robotics in NPPs followed by description of existing systems in Section II. The associated key challenges are mentioned in Section III while Section IV depicts future directions. Finally Section V comments on conclusion.

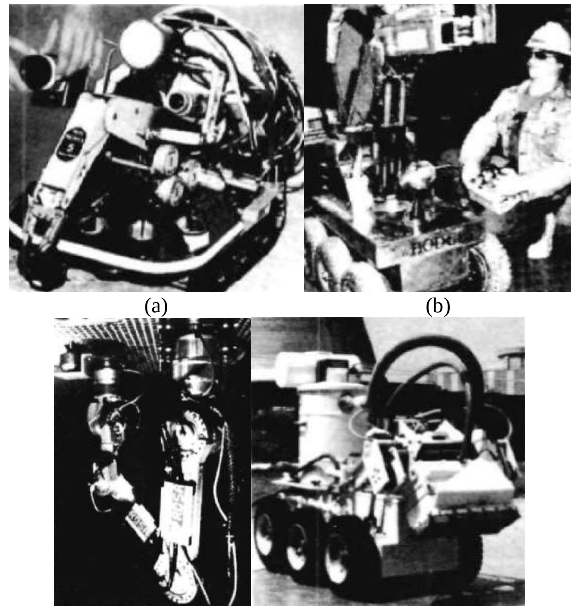
II. Robotics In NPPs

Robotics technology in NPPs was first implemented in US for radioactive material handling. The robot developed by Hughes Aircraft in 1958 was one of the foremost typical applications of robotics technology to reduce human risk associated with the contaminated hazardous environment [3]. Industrial robotics was a new research field at that time. In early 1980's, advances in robotics technology and emergence of new generation of control systems made it possible to offer applied solutions for the nuclear power industry.

Robotics technology in NPPs can be categorized into mobile robots and manipulator based robots. Hybrid of these two groups is also common in nuclear industry.

A. Mobile and hybrid robots

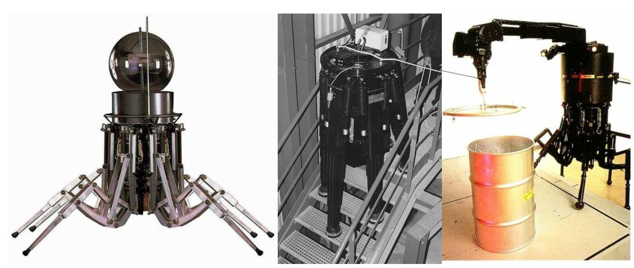
A strong drive to opt for advanced robotics in nuclear industry was established by challenges arisen in the NPP catastrophes like incident at TMI 2 reactor. A number of robots were developed and deployed years after the incident. After three years of the accident, a System in Service Inspection (SISI) remotely controlled mobile robot was used for the inspection of the troubled zone [4]. The robot televised photographs from the contaminated zone, collected samples and radiation readings for further testing. Fred, a heavy six-wheeled mobile unit was the second robot which was sent to swab the surfaces in the contaminated area equipped with high pressure hot water. To defuel the reactor core, a remotely controlled manipulator, Rosa, was employed. Moreover a series of three Remote Reconnaissance Vehicles (RRV) was deployed for inspection, surveying and cleaning operations. For the most contaminated zone in the basement of reactor, a RRV the "Rover" was engaged. Rover was designed for the radioactive inspection of the basement with the help of television cameras and instruments mounted on the robot. The second RRV was used in various parts of the reactor building to remove the radioactive deposits while the third RRV was designed to dismantle small structures in the building and to collect contaminated samples especially from the basement of the reactor. Robotics technology in fact made it possible to visit a 'no go' location. Electric Power Research Institute (EPRI) was the principle contributor in that achievement. Figure 2 shows some of these robots.



(a) (b) (c) (d)

Fig. 2. Robot for NPPs: (a) SISI (b) Fred (c) Rosa (d) Remote Scrabble

Odetics with the contribution of EPRI designed and developed another powerful mobile robot, "Odex" capable of fast movements, 360° spinning and obstacle avoidance yet lifting as heavy loads as five and a half times of its own [3]. This strength-to-weight ratio was an astounding innovation with no prior example in the history of robotics. Odex-I was a hexapod (also known as 'Functionoid') mobile robot with remote assistance for maneuvering. It has redundant control system with self-regulating microprocessor for each leg and a central computer control for overall actuation. The motions were produced by 18 motors: three motors dedicated for each leg. The Odex-I (Figure 3a) was designed without any demarcated applications. Odex-II (Figure 3b) was the redesigned model with an addition of an extendable arm. This new machine was designed for Seventh River Nuclear Labs for sealing contaminated waste material containers. Odex-III (Figure 3c) with modified leg design, offered improvements in terms of payload capacity, environmental hardening, sealed mechanisms and wide range of tools [5].

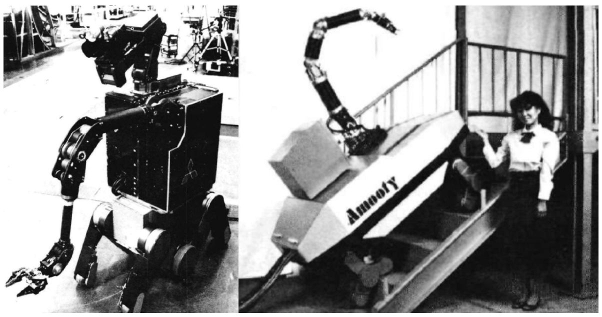


(a) (b) (c)

Fig. 3. Robot for NPPs – Odex: (a) I (b) II (c) III

General purpose robots developed in Japan with high reliability and mobility can find potential in fueling, inspection, decontamination and maintenance applications in NPPs. A fuel handling remote unit [6] has been deployed at

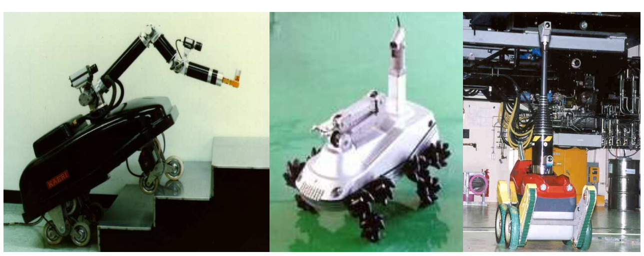
Tokoi plant. The robot is equipped with a fuel basket gripper supported by a telescope. An inspection unit with a flexible arm was used to take wide view of the field inside the cell. Power reactor and nuclear fuel development corporation (PNC) developed a two-arm manipulator (Figure 4a) capable of bilateral actuation with servo mechanism for HLLW plant [6]. Amooty, a general purpose robot (Figure 4b) by Toshiba was capable of climbing stairs [6]. Equipped with TV cameras, the robot was designed to maneuver inside a plant subject to availability of the map. Other general purpose robots were Crawler by Hitachi and One-Armed robot by Mitsubishi.



(a) (b)

Fig. 4. Robot for NPPs: (a) Two-arm manipulator (b) Amooty

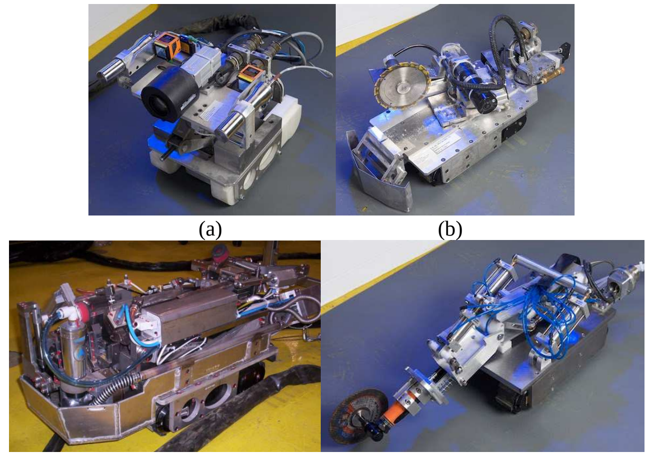
A series of mobile robotic platforms KAEROT (Figure 5a) have been developed by Korea Atomic Energy Research Institute (KAERI) for maintenance of reactor coolant system during refueling outage. The system [7] is a four wheeled robot with zero turning radius and stairs climbing ability. A manipulator is mounted at top of the robot for inspection and maintenance purpose. KAERTO m2 (Figure 5b) is an enhanced version having planetary omni-directional wheels and a 6 DOF manipulator. KAEROT m3 (Figure 5c) designed with larger wheels and four tracks is intended for pipes and tubes inspection using Infra-Red (IR) vision. Another tele-operated robotic system evolved in KAERI with the intention to clean and decontaminate high radiation field is presented at [8].



(a) (b) (c)

Fig. 5. Robot for NPPs – KAEROT (a) m1 (b) m2 (c) m3

Researchers at Kinectrics Inc., Canada developed a novel remote robotic system [9] comprising of four robots to extract high-activity debris from a nuclear heat transfer system. These robots (Figure 6a-d) which work in series include: Gamma probe and camera robot, Insulation removal robot, Pipe removal robot and Contingency robot.



(a) (b)

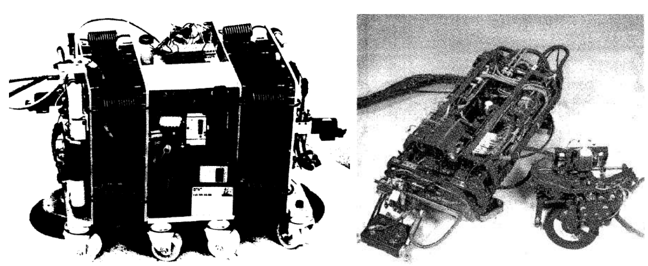
(c) (d)

Fig. 6. Robots (a) Gamma probe & camera (b) Insulation removal (c) Pipe removal (d) Contingency

One of the latest robotic systems realized at MIT to replace human inspectors in hazardous environment uses a spherical shaped robot (Figure 7) which can change its orientation like an eyeball using a novel proposed mechanism [10]. The developed prototype may navigate underground pipes of a nuclear reactor using a pair of thrusters.

Fig. 7. Eyeball ROV prototype

Operations in NPPs can be made safer and secure by deploying climbing robots having vertical maneuvering capability. Briones et al. [11] proposed a pneumatically actuated robots – Robicen (Figure 8a) that uses suction pads for NPP inspection remotely. Another robot named as SADIE (Figure 8b) has been conceived to inspect welding of gas ducts in NPPs [12]. These uses vacuum gripper feet and a sliding frame mechanism.



(a) (b)

Fig. 8. Climbing robots: (a) Robicen (b) SADIE with tool packages

B. Manipulator based robots

An Articulated Inspection Arm (AIA) was developed by CEA with an ability to perform under the in-process temperature, pressure and other conditions [13]. This arm was particularly realized for inspection and maintenance of the vacuum vessel without shutting it down. AIA (Figure 9) is a multi-link cantilever based arm with 8 DOF and a payload capacity of 10 Kg.

Fig. 9. AIA with the viewing system inside Tore Supra tokamak

Researchers at Engineering Services Inc. (ESI) realized a manipulator named AARM (Figure 10) for inspection of nuclear reactor components and parts [14]. This is a remote control manipulator having 4 DOF. The main novelty of this development is the joints design to accomplish required task successfully. The system is operational at CANDU 6 facilities.

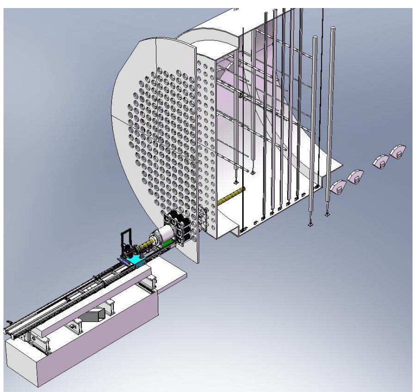


Fig. 10. Schematic view of AARM inserted in the vessel

Another remotely controlled manipulator installed by Atomic Energy of Canada Ltd. was equipped with an imaging system to weld the pipe leakages in Douglas Point reactor [15]. Other automated/remotely operated dismantling and handling units for same applications have been developed in Germany for KernKraftwerk Niederachbach (KKN) plant.

Remote control tasks in NPPs include almost all kind of operations. These include material handling, material inspection, site inspection, parts assembling and dismantling, repair and replacement of components, underwater applications and fabrication processes. For remote control manipulation, different techniques which are in practice comprise very basic master-slave configuration, electric direct wiring, radio control and laser beam and computer aided servo manipulation in master-slave configuration. A case study considering the application of a new design of remote handling systems to two different tasks within BWR and CANDU reactors is presented at [16].

For decommissioning in high radioactive zones, Automated Guided Vehicles (AGV) with specially designed tracks and wheels under the floor are used. The vehicles are equipped with manipulating arms and instruments to perform recovery activities. Such vehicles are specifically studied by Commission of the European Communities (CEC) from NPPs viewpoint.

For remote maintenance and decommissioning tasks, computer aided servo-manipulator system supported by TV cameras and telescopes have been realized in France [15]. Such manipulators are capable of working as a remotely controlled mechanism as well as an independent robotic system.

For material handling and transportation, fueling and site inspection activities, researchers from SPAR Aerospace Canada (now MacDonald Dettwiler) developed remote manipulator [15] control system equipped with a Remote Manipulator Subsystem (RMS) furnished with an arm. This system was based on the SPAR technology with an aimed application of re-tubing at Pickering reactors.

III. Key Challenges

The primary challenge of robots in NPPs is to ensure safety with precision, reliability and repeatability for any kind of operation in any state at any time under any circumstances. This challenge has been in focus in research community from 80's as discussed in [3] but due to technological limitations in terms of on-board processing speed, power requirements and unavailability of integrated sensors and actuators, initial robotic systems were highly task specific with little intelligence. The robots were almost unable to cope with any other scenario for which they were not designed. The robotic units were designed with stationary bases and with specific and limited work space. To accomplish complex tasks, researchers at that time preferred using tele-operated robots in NPPs rather than enhancing intelligence in autonomous mode to avoid undesired results. Despite of these limitations, still robotics were used in NPPs. The development of integrated circuits in 90's significantly facilitated building of various kinds of robots for NPPs with more autonomy. The trend from stationary robots was shifted to moveable robots equipped with integrated manipulators. These advancements though permitted accomplishment of various tasks in NPPs using robots but posed a great challenge in terms of increased system complexity.

To make use of nuclear power for the benefit of human being in a risk-free and undisruptive manner is another challenge. This key rationale actually wrap up all efforts being made to make nuclear plants a secure power resource. To achieve this status, in addition to development of superior state-of-art technology, we need to devise better plans and systems to cater for cataclysmic circumstances.

NPPs fall into sensitive category requiring robust operational monitoring and precise control. For proper and safe operation, NPPs have to follow very strict SOP in all steps throughout the year. Plant activity could be characterized under two states: (a) Normal operations in which monitoring and control with periodic inspection and maintenance cycles are executed. Each section of NPP may require different time schedules for maintenance cycles as per nature of process involved. Systems conceived by Caprari et al. [17] and Lee et al. [18] are intended for normal operations of NPPs. (b) Emergency operations which require rapid surveillance, rescue, fault finding and maintenance in a systematic way to ensure safety of humans and plant.

NPP consist of different sections integrated with one another for reliable operation. Figure 11 shows simplified block diagram of NPP. The possibility of occurrence of an emergency in a part of a plant demands particular procedures to be followed based on the functionality of that specific part. Robotic systems are designed based on the detailed analysis of worst-case scenario in a specific part of a plant, thus presenting a great deal of design challenge.

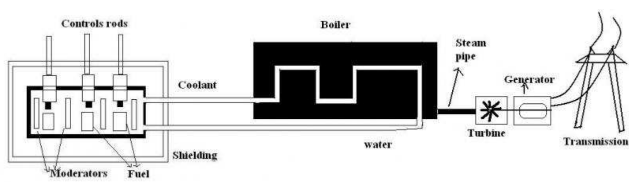


Fig. 11. Simplified block diagram of NPP

Reactor with cooling towers (shown in left) is the most sensitive part of a NPP. Radiation danger in these parts imposes special attentions for all kind of operations in this region and thus this is probably the most desired area of deployment and use of intelligent robotic systems. The challenges in this particular region are coped using various existing branches of robotic units such as mobile robots, stationary industrial arm manipulators or hybrid robots. For example, a state-of-art mobile robotic unit integrated with perception sensors and equipped with navigation capability can be first choice to monitor different parameters (such as radiation level) inside the reactor or cooling chamber instead of humans. For maintenance operations of different kinds of valves, piping etc, special manipulators with high dexterity can be used either autonomously or in tele-operation mode. Other parts of NPP are boiling and power generation chambers. Though hazardous radiations are small in these parts but due to sophisticated machinery, continuous observations and maintenance is required.

Any particular operation in industry is carried out by trained work force. Intelligent robotic units are designed and tested on the principles similar to that of human work force. However in case of humans, due to their intelligence and multi DOF, they can accomplish tasks in unexpected situations with minimum training or without training by following some common understanding. Unfortunately till now, this is not the case with robotic units. This is a general challenge in robotics which also constrains the use and performance of robots in NPPs.

IV. Future Perspectives

Utilization of robotic technology in contaminated zones as tele-operated as well as independent manipulators and mobile robots to handle high risk movements has appeared as an obligation. With the advancements in mechatronics, it is appreciable that efficient solutions are evolving in market very rapidly. Scientific community is witnessing immense progress of intelligent robotic units to help humans to make NPP operations secure and reliable. The robotics technology serves in this regard with a commendable track record and brilliant future prospect.

Current strategies in NPPs are usually based on the idea to have a specific robotic unit for a specific job. Due to variety and versatility of tasks performed by robots in various parts of a NPP, future plants will employ more intelligent and functionally complex robotic solutions. Future NPPs are expected to deploy multi-task oriented robots that can perform many activities with intelligence and have the capability to tackle unwanted situations. Just like humans, robots may need minimum training for task accomplishment in future by exploiting more sophisticated level of Artificial Intelligence (AI) and data fusion. Advancement in computer vision will further facilitate the implementation of optimized navigation and localization algorithms for efficient operation of search and rescue robots in NPPs.

To properly cater the radiation emissions in NPPs, robots will use new materials to maintain unaffected operation of electronic devices. Furthermore, next generation robotic systems in NPPs are expected to work efficiently in full autonomous mode in contrast to the current man-operated or semi-autonomous scenarios. To be able to respond in a more timely fashion to avoid or control any entropy, NPP robots will be more robust. Other novel research in areas like haptics, coordination among multiple robots in a SWARM like fashion and robot learning together with advancement in onboard computing, sensor technology and powerful batteries could also be potentially useful for NPPs in future.

Far future systems may deploy humanoid robots in NPPs as well. This is not so straight-forward as there are many hurdles in front of researchers. The biggest being is the lack of complete functionality understanding of human brain. Moreover humans are blessed with so many functions which are difficult to duplicate. Researchers are successfully progressing to replicate simple functions. Superior mechanics and materials would make it possible to develop compliant human like leg and hand structures for proficient motions. Who knows that future versions of humanoid robots like ASIMO, NAO, TOPIO, iCub can be a good potential candidate for NPPs.

V. Conclusion

Robotics technology and automation techniques are serving NPPs avoiding human exposure to an unhealthy environment. The tendency of development of specific robotic units for NPPs seems to be more accidental oriented rather than pre-planned designs for reactor operations. This trend needs to be rectified to achieve efficiency both in NPPs' operations and robotics technology. We expect to have enhanced role of robots in NPPs of future.

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VII. BIOGRAPHIES

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