Application and Standardization Trend of Maintenance and Inspection Robot (MIR) in Nuclear Power Station

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Abstract. With the continuous construction of nuclear power station and the great public attention to the nuclear safety, developing robot of nuclear power has played an important role in the nuclear industry. Also it is the global focus on daily monitoring, maintenance and other complex operation by robot technology in nuclear environment. This paper introduces the current research and application of Maintenance and Inspection Robot (MIR) in nuclear power system both at home and abroad, and then analyses the standardization development trend of MIR.

1. Introduction

Nuclear energy is the only energy that can almost fully replace fossil fuels, and it is also one of the important methods to realize sustainable energy development. In recent years, many countries have put forward energy strategies to promote nuclear power to meet the growing demand of national economy and social development. At present, China has become one of the largest nuclear power construction countries in the world. And 13 nuclear power stations and 58 million kilowatt nuclear power units will be built by 2020 in China [1]. So it is developed from suitably to positively [2], as shown in figure 1.

![Figure 1. Growth trend of Nuclear Power Station in China.](image)

However, when people are using the huge energy generated by nuclear power, they are also deeply influenced by the potential threat of radiation leaks. Therefore, the issue of Nuclear Security became a global focus again especially after the explosion of Japan Fukushima nuclear power station in 2011 [3-8].

High radiation dose and complex structure environment are the main problems in nuclear power station. Operators will inevitably be exposed to nuclear radiation during routine operation, which...
poses a great threat to their life security. In this particular environment, using robots to replace operator can reduce the labor intensity and radiation dose, and improve the efficiency of station maintenance and accident treatment. So it has become the industry consensus to use robots in the station instead of operators [4]. Robots, especially MIR, play a most important role in nuclear power industry because of the prevention principle. This paper mainly describes the application of maintenance and inspection robots in nuclear power station at home and abroad.

MIR is a specialized robot, which executes the mission to explore and emergency handling in the radiation environment instead of operators. It can provide detailed and accurate technical basis to find out the accident source term information, to evaluate the accident consequences, to decide the emergency protection, to formulate a scheme and to adopt restoration measures, which is of great significance to nuclear emergency work, especially daily monitoring of emergency rescue and radiation for civilian and military nuclear facilities.

2. The development of MIR both at home and abroad

Monitoring and maintenance of nuclear facilities is the earliest application target of nuclear power robots [4]. Because people are unable to enter the nuclear reactor sealed container to inspect important equipment when running, so the task must performed by robots.

2.1 MIR development in foreign countries

Back to the 1980s, countries such as the USA, Japan, France, Germany and other countries conducted research on detection and routine maintenance robots, and developed a range of products.

2.1.1 MIR in USA

The remote control manipulator, called M1, was developed in Argonne National Laboratory (ANL) and firstly used in nuclear industry [5]. It can be used to operate radioactive substances and effectively reduce the dose of people's exposure.

After that, Odex series robots were developed by American Odetics Incorporated Company, which were six-legged walking robots [4-5]. It can move freely on the flat surface, and perform maintenance operations by its small manipulator. And the robot can go through the narrow place if folding the mechanical arm into the robot's diameter profile.

ROSA series robots, developed by Westinghouse Electric Company, were used for maintenance and inspection of Steam Generators (SG) in nuclear power stations, and the functions of small size leak repairing and its effect testing were also included [4-6]. ROSA III, shown in figure 2a, can provided long-distance maintenance checks for high radiation areas additionally. It can complete six axial movements and carry about 80 pounds payload.

Furthermore, robots, named T-crawler, FlangeBot, Genesis 2000 and Pegasys, developed by Westinghouse Company [8]. COBRA robot of Framatome-ANP (Advanced Nuclear Power) in Virginia [9] and ZR-1 robot of ZETEC Company [10] can mainly maintain and inspect the SG as well. Among these robots, Pegasys, shown in figure 2b, is a simplified tube-plate crawling robot, which can grip the tube plate alternately by two sets of pneumatic feet, and carry the tools to inspect the tube of SG and operate blockage. Pegasys is easy to operate on site, and its control system is simple in maintenance. Multiple robots can be placed at the same time to reduce collection time for its small size and light weight. At present, SUPREEM system made in Westinghouse Company is more popular in American power plants [11]. It contains two installation platform, on which equipped with two six-axis manipulators respectively, to complete container inspection in 3.5 to 4.5 days. Also, the system can carry a series of ultrasound and eddy current probes to meet specific needs, and has been used to inspect nuclear power station in UK, Sweden, China, South Korea and Germany.

A kind of strong radiation environment detection robot, named SURBOT (seen in figure 2c), developed by American REMOTEC Company is able to move and steer flexibly through wheels driven by two motors installed at the bottom and a free flywheel. Thus, the robot can enter the rooms
flexibly and circularly to detect the environment of nuclear power station when deploying and retracting the cable automatically driven by robot’s movement [12].

Recently, a snake-like robot (seen in the figure 2e) developed by Carnegie Mellon University (CMU), is composed of 16 modules, and its size is 37 inches long and 2 inches wide [13]. Currently, it was tested in an Austria nuclear power station. There is a camera and a LED light on its head, and through which internal video is obtained. So researchers can observe the situation in piping, valves and containers and analyze the internal consumption. The deepest pipe that the robot has climbed in tests was 60 feet.

Robots PackBot and Warrior (shown in the figure 2d) are produced by the famous robot research company iRobot, which played an important role in Fukushima disaster [14]. PackBot is a light-weight robot which can transmit real-time images and environmental data including oxygen content, temperature, gamma radiation and dangerous chemicals through hundreds of optical fiber. While Warrior is a middle-sized robot which is used to clean up the radioactive obstacles in the accident scene and whose maximum load is 90 kg.

In 2000, explosive-handling robot Talon (shown in the figure 2f) developed by Foster Miller Companies is to help the US Army to deal with explosives [15]. It is also suitable for the need of nuclear environment monitoring through the proper modification. And its detection system can measure gamma rays dose rate from 30 kev to 1.3 MeV while the full range is 3 Gy/h to 10 Gy/h. Thus, threat of radioactive materials can be effectively disposed in a nuclear accident and emergency rescue.

![Image](image.jpg)

**Figure 2. Part MIR in USA.**

a. ROSA III b. Pegasys c. SURBOT d. PackBot and Warrior e. Snake-like Robot of CMU f. Talon

2.1.2 MIR in Japan

In Japan, the first bipedal robot used for inspection of nuclear power station was developed by Waseda University in 1977, which can complete valve inspection and switch, radioactive water treatment and other operations. The dual-arm robot (seen in the figure 3b) used for nuclear equipment maintenance and testing was developed by Sugiyama [4,46], which can operate 10kg items by remote control and the maximum load is 250kg. A kind of module replacing robot for 4 tons tank produced by
Takeo was for the Project of International Thermonuclear Experimental Reactor (ITER), which can work in both compact and wide spaces because of the adaptive manipulator with two Kinematic pairs and 6-DOF [16].

Nuclear station inspection robot was made by Japanese Nuclear R&D Center cooperated with power plants for PCV (Primary Containment Vessel) environment, which was equipped with a microphone, infrared cameras, temperature sensor and other sensors to detect the information about pipeline leak, switch valve, pipeline corrosion, environmental change, abnormal sound, abnormal smell, abnormal temperature through the processing data originally obtained from multi-sensors [17].

In 1999, a kind of dual-arm remote-controlled robot, called RaBot (shown in the figure 3c), was intended for Aichi accident by Japan Atomic Energy Agency (JAEA), which can open and close the valve in radiation field.

A radiation detection robot, Monirobo (in the figure 3d), was successfully developed by Japan's Nuclear Safety Technology Center in 1999, whose size is 800 * 1500 * 1500 mm and weight is about 590.2 kg. It can walk 40 meters per minute driven by two crawler wheels, and was equipped with mechanical arm for obstacles removing and sample collecting. The red Monirobo A robot was installed with radiation detection, 3D cameras and temperature and humidity sensors mainly to inspect while the yellow Monirobo B robot was used for collecting dust samples and detecting flammable gases. They were both anti-interference for their radiation shield on the surface and the
operating distance was up to 1.1 km. But Monirobo robots were not applied to Fukushima accident because of radiation leaks neglect by Japanese government at the moment [4, 18-19].

After Fukushima, two small robots Tsubake (in the figure 3e) and Sakura were developed by Japan Mobile Robot Research Institute. Tsubake can climb the stairs when loading a heavy gamma ray detection device, so it can carry 50kg measuring equipment to the contaminated area to collect data. Whereas, Sakura is smaller, whose function is mainly carry a camera and a thermal imager into the radiation area freely upstairs and downstairs in narrow spaces to transmit real-time video signals. The robot Quince (in the figure 3g) from Japan's Chiba Industrial University was also involved in the rescue work of the Fukushima accident, which was mainly used to measure the radioactivity level and return the live images [20].

A patrol robot TOSRIS for nuclear power station developed by Japanese researchers Katsuhiko Satoh, was equipped with a variety of sensors including temperature, vision, auditory, contact and vibration, laser rangefinder, ultrasonic rangefinder, and etc. [12, 21]. An optical wireless transmission device is applied to realize the communication of sensor information and remote console. And TOSRIS can realize routine inspection according to the schedule and respond appropriately to the abnormal as well because three sub-systems of autonomous motion, remote sensing measurement and fault diagnosis are integrated effectively.

Meister (in the figure 3h), a robot available working in severe environment, was manufactured by MHI in 2012 to replace human access to the leaky nuclear power station [22]. It was about 440kg weight, and can move at the maximum speed of 2 km/h with the aid of four crawlers. It had two mechanical arms controlled by 7 axes that can install multiple tools to perform different tasks in narrow spaces, like drilling holes in concrete walls and taking out samples, and the maximum load was 15kg.

Two mobile robots, SMERT-M and SMERT- K, were produced by Japanese Toshiba Company to realize information collection quickly in emergency areas [23]. SMERT-M was a dual-track mobile robot equipped with sensor units, expandable mechanism, multi-axis robotic arms and a ramp to carry SMERT- K. But SMERT-K was a small wheeled robot that can move quickly and flexibly within narrow spaces. Another Tetrapod robot (seen in the figure 3k) was developed in 2012 to mainly use for radiation information collection in the Fukushima nuclear power stations [3].

2.1.3 MIR in France

Robots MA23-SD [12] and ROGER (in the figure 4a) [24] for nuclear reactor and SG overhaul respectively in France had get a great progress in remote control and can do tele-operation to nuclear waste based the force feedback. Robert LMF, made by CYBERNETIX Company, can move smoothly in horizontal direction, cross about 1000 mm wide trench and climb 400 mm high stairs by the traditional double-tracked travel mechanism mounted another 4 rail legs. It was mainly used for nuclear facilities monitoring, inspection and maintenance, and also for handling equipment and clearing the debris.

Robot RICA2 (in the figure 4bc) produced by French SRA-SAVAC Company was able to conduct radioactive detection for hot cave that nuclear shielded, and on which installed a lamp capable of 360-degree rotation, zoom camera, measuring instruments and other equipment.

In addition, the MIR used for the Phoenix Reactor (Fast Reactor) in France was able to check the weld seams of the pressure vessels and conduct ultrasonic test as well [25].
Remote-controlled robot Telbot, produced by German Hans Walischmille Company, had been used for inspection and repair of SG in nuclear power stations in Canada and Japan from [4].

OFRO robot (in the figure 5a) developed by Berlin Robowatch technology company in 2006 was mainly used for patrol inspection work in the stations, which equipped with the infrared camera, CCD camera and microphone, to collect ambient air samples automatically, and transmit the corresponding data information through radio to security staff in time from [26].

A robotic snake (in the figure 5b) created by British OC Robotics Company was flexible enough to bend as required to reach areas while other robots were unavailable from [27]. The snake was controlled by a group of hinged wires that like muscle tendon. Various tools was installed in the end of effector while all the engines and transmission devices was located in its base. The snake has now been applied to overhaul nuclear facilities in Sweden, and conduct safety inspection in a Canadian factory with 70kg weight, 50 mm per second speed and 0.1mm positional accuracy.

Robot INSIS-EC made by Indian Nuclear Power Company is the first wideband eddy current inspection equipment in India, one end of which is fixed to the inlet hole of the flange and the other is a working part from [28]. Working data can be transmitted to the control station faraway with the camera and cable.

The multi-functional robot SECURITAS (figure 5c) working in nuclear environment was successfully developed by Ario Romiti in Italy from [12]. It was actuated by 4 small track below which driven by two 1000W motors, and the application of differential gear to solve the problem of a motor driven two tracks at the same time. The robot can climb up to 45 degrees of slope, over the 230 mm high step, and carry 300kg payload with a maximum operating speed of 0.3 m/s.
Overall, MIR is a special robot and mutually-different generally. Therefore, researchers around the world nowadays, including the United States, Japan, France, etc., are in the robot research of nuclear environment, and strive to develop various robots to meet the specific needs in site.

3. MIR Development in China

Research on nuclear industry robot has begun since mid-1990 in China as well, including Shenyang Institute of Automation, China Institute of Atomic Energy, Harbin Industrial University, the fourth nuclear power plant, etc., and has obtained definite research progress. However, the relevant research results had not been applied and spread because of budgets cut in the nuclear arms industry and slow development of civilian nuclear facilities. In recent years, application research on radiation monitoring instrument and robot has carried out following up the international nuclear technology by China Institute of Atomic Energy, Institute of High Energy Physics, Institute of Chemical Defense, the Second Institute of Nuclear Energy, the First Institute of Nuclear Energy, Shanghai Institute of Nuclear Engineering, Tsinghua University, Beijng Normal University, Beijing university of aeronautics and astronautics, and etc with the support of the Ministry of Science and Technology and the General Armament Department.

Robots SGR-1 and PRR-1 for maintenance and inspection of steam generator (SG) and stabilizer (PR) separately were developed by Shanghai Jiaotong University joint several universities from [4]. A prototype of remote controlled robot, called Warriors, was also manufactured by them to conduct radiation decontamination, sample collection and maintenance with ‘car-hand’ combined mechanism and caterpillar motion structure, which had working abilities in complex environment such as spot turning, walking up and down stairs, and crossing the trench. Double-armed structure was designed to expand operating areas and raise the load capacity with 1.5 m expansion and 10kg payload per arm. The position and posture of the clamps at the end can be controlled flexibly due to 6+1 freedom per arm.

A patrol robot (in the figure 6a) for nuclear power station made by Shandong Luneng Group used multi-sensor technology of remote infrared thermal imaging, sight, sound and so on, to find the problems of nuclear facilities like hidden troubles and internal thermal defects by independent or remote real-time inspection [29].

A radiation detection and emergency robot (in the figure 6b) researched jointly by China Institute of Atomic Energy and Beijing University of aeronautics and astronautics, carried radioactive source "hot spots" imaging device with 360 ° circumferential observation and -10 ° to +10 ° pitch observation to obtain high-resolution images of degree of radioactive pollution [30, 31]. And its control system adopted stable and reliable embedded design to control redundance directly, and can be controlled separately by special console and computer through wired and wireless communication mode.

Robot SJTU (in the figure 6c) developed by Special Robot Laboratory of Shanghai Jiaotong University was especially used to detect and repair the equipment of nuclear facilities for radioactive scene such as nuclear power station, nuclear fuel reprocessing plant, and waste treatment plants [30]. Spot turning in 70 cm radius was available with the crawler-and-arm structure, ability of bidirectional force feedback was provided to perceive force information of operator with sensor integration system.

The underwater salvage robot (in the figure 6d) with the key technology of dynamic and static sealing in high radiation environment was developed by Institute of Optics and Electronics, Chinese Academy of Sciences in 2006, which was the first one produced independently by domestic researchers and had applied to Daya Bay station on trial [32-33]. It was composed of underwater crawling vehicle, 2-dimensional holder, manipulator, sweeper, underwater pump and controller, whose monitor system included TV camera system connecting with image compression storage system through 30 m cable. Among these components, manipulator was used to handle larger falling objects such screwdrivers, sweeper can clean up smaller items such as screws, and underwater pump was applicable to clean tiny objects like slag, debris, etc. The manipulator is used to handle larger falling objects such as screwdrivers. Cleaning machines can clean up smaller items such as screws,
etc. The underwater suction pump is used for the cleaning of small objects, such as slag, debris, etc. The robot system was a multi-disciplinary cross connection system which combined with technologies of optics, automatic control, precision machinery, information processing and system integration.

A six-wheeled remote-sensing robot (in the figure 6e) made by China Institute of Radiation Protection was able to do detecting operation in the high-radiation field where gamma dose rate was below 100 Gy/h from [30]. It was composed of walking mechanism, electric holder and detecting device. And over-obstacle ability was improved due to the two front wheels which can vertical swing 90°. A six-wheeled remote-sensing robot (in the figure 6e) made by China Institute of Radiation Protection was able to do detecting operation in the high-radiation field where gamma dose rate was below 100 Gy/h. It was composed of walking mechanism, electric holder and detecting device. And over-obstacle ability was improved due to the two front wheels which can vertical swing 90°. Wired and wireless communication methods for remote control were taken to feedback the real-time scene image and radiation information of the strong radiation environment. A radiation resistant camera mounted at the top joint of electric holder can photograph the spot in multiple directions with joint turning control in order to know the site conditions of accidents clearly and comprehensively.

Nuclear detecting robot (in the figure 6f) made by Southeast University with several institutes was equipped with cameras, ultrasonic and infrared distance sensor, wireless communication system, radiation detectors, and etc. [34-35]. It can enter into high-toxic and high-risk areas deeply to execute detection, sampling and emergency tasks of radiation, chemical and biological pollution.

A nuclear emergency disposal robot (in the figure 6h) invented by Special Robot Laboratory of Southwest University of Science and Technology has successfully processed the two source-blockage accidents of Qi county in Henan province and Panyu in Guangdong province, and the robot system accumulated up to 700 KGY irradiation dose [29, 36-38]. A kind of video monitoring system (in the figure 6g) for strong radiation environment from the laboratory can be widely applied to the radiation field, such as irradiation plant, nuclear tests and nuclear radiation research center, to complete the real-time monitoring tasks by safe, reliable and remote video control [39-40]. The improved version of the system has been used for inspection of cable trench.

Figure 6. Part of MIR in China.

a. JP-DZ-06 Robot from Shandong Luneng Group  b. Radiation Detection and Emergency Robot from CIAE  c. SJTU Special Robot from Shanghai Jiaotong University  d. Underwater Salvage Robot from Institute of Optics and Electronics  e. Remote-sensing Robot from CIRP  f. Nuclear Detecting Robot from Southeast University  g. Video Monitoring System from SUST  h. Nuclear Emergency Disposal Robot from SUST
The robot family, led by China Guangdong Nuclear Power Group, has partially implemented engineering applications. Among them, the reactor pressure vessel NDT robot (in the figure 7f) and miniature submarines (in the figure 7c) belong to MIR series robots [41-42]. The former uses nondestructive testing methods like ultrasound, video, and so on, to inspect weld of nuclear reactor pressure vessel shell and pressure vessel nozzle before and in service, and will be applied to the Taishan nuclear power units. The latter is an underwater and video inspection robot for reactor pool, core, spent fuel pool or primary circuit pipelines of nuclear power station, which has been successfully applied on the SG simulation body in the Daya Bay station.

Overall, China's nuclear power robot has made great progress promoted by the global requirements and strong support from China’s government since 1990s. However, MIRs mainly developed by research institutes and universities is difficult to industrial application for its late start in China, relative small market needs of special robot, and lower reliability of some parts. With successive construction of nuclear power plant, robots are increasingly needed for China's nuclear industry. Therefore, MIR development in industrial application will be great accelerated, which will encourage more domestic researchers and enterprises devoting themselves to MIR technology.

Figure 7. The Robot Family from China Guangdong Nuclear Power Group.

a. Refueling Robot  b. Side Block Operation Robot  c. Tiny Submarine Robot  
d. Multi-functional Underwater Robot  e. Integral Bolt Drawing Robot  
f. NDT of pressure vessel Robot

4. Summary

Nowadays, a variety of nuclear robot, whose quantity has reached thousands or even ten thousands in the whole world, mainly realized the functions of nuclear equipment condition monitoring, routine maintenance and emergency treatment known from the above investigation of MIR development of domestic and overseas. These robots are generally quite different, and usually designed by cooperative robot manufacturers specially for the requirements of the certain nuclear power enterprise. So the performance is decided by enterprises themselves. So the robot is specialize and costly but poor-popularized because it can only use in the certain nuclear station while working in other stations is unavailable. Several robots failed their tasks in Fukushima leakage accident in 2011 related to the strong radiation and the complexity of the post-disaster environment, but defects was reflected
indirectly on the environmental adaptability requirements of robot design. Also strict standardization of testing and detecting was deficient.

Although a technical standard for nuclear power robots has not been formulated in the world now, relevant technical standards and test specifications have been developed in the field of industrial and service robots. So it is necessary to standardize nuclear robots due to a certain amount need in the world even its application is relative smaller than industrial robots.

Therefore, advantages are in the following if corresponding standards for nuclear power robot can be set up.

(1) It can provide normative guidance for the whole design and testing process of nuclear power robot, which is beneficial to ensure the performance and reliability of the final product.

(2) It can provide unity criterion for its manufacture and experiment testing, which is helpful to optimize the robot manufacturing process and quality control. Meanwhile, it puts forward specific technical requirements for robot suppliers and manufacturers rather than doing useless repetitive technical work.

(3) It can set up relevant technical barriers for the import of nuclear power robots, and provide some opportunities for the rapid growth of domestic robots.

(4) It is conducive to the rapid introduction of new technology, and benefit to the rapid improvement of the automation of nuclear power equipment so as to realize the high-quality and orderly development of the nuclear industry.

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