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Visual inspection
Better than your eyes

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Abstract

Ongoing improvements in the development of camera technologies and manipulator techniques permit an enhanced performance of inspection tasks in nuclear services. In areas of reduced dose rate it`s possible to use small size high resolution CCD cameras instead of tube cameras. Underwater inspections may be performed by submarine instead of rigid manipulator systems. This allows the enlargement of inspection areas and the performance at reduced time and personnel dose rate

1 INTRODUCTION

Hardly any technology in the world has experienced such rapid advances in recent years as visual inspection techniques for industrial plant maintenance. This especially applies to inspections at nuclear facilities where a particularly high level of reliability and precision is required of such methods.

Advances and improvements have focused not only on the actual cameras themselves but also on the manipulator systems which are so essential for any detailed, reproducible inspections, especially underwater.

Today's cameras and manipulators are now often found combined into a single unit and are increasingly being used for other applications besides visual inspection.

2 DEVELOPMENT OF CAMERA TECHNOLOGY

In the field of underwater inspections at nuclear plants, one only needs to go back ten or fifteen years to find the first projects involving visual inspection equipment. At that time, commercially available tube cameras had to be specially designed for deployment underwater in what were sometimes extremely high radiation fields. The demineralized water used in nuclear power plants imposed a special set of requirements right from the start as far as leak-tightness of the camera housing was concerned.

Figure 1: Early-generation tube camera

It was not just the size of these cameras – the smallest ones still had a diameter of over 50 mm and were approximately 350 mm long – but also the cumbersome umbilical carrying the camera signal, control and lighting cables that greatly limited deployment options. In addition, the low light sensitivity of around 10 lux made it necessary for the object under inspection to be additionally illuminated using separate, high-intensity light sources. Furthermore, images were only available in black and white, thus limiting the information that could be obtained from them.

In the early days, problems arose in connection with the leak-tightness of the camera housings, especially when used in demineralized water. This resulted in special requirements having to be met by the camera's plug and screw connectors. The cameras as a whole and the individual tubes themselves therefore needed frequent repairs. Considerable expense was involved not only in purchasing the tube cameras but also in maintaining them. However, the tube cameras' relatively high radiation resistance of 2.5×10^6 rad/h is an advantage compared to the current generation of CCD (charge-coupled device) cameras providing a similar degree of resolution and is one of the main reasons why they are still being used today in certain areas.

Nowadays, for visual inspections in nuclear facilities, modern CCD cameras are deployed both underwater and out of the water. This field has been subject to an extremely fast rate of development in the past ten years – changes that have affected nearly all features of this technology and can be expected to continue without respite in the future.

The exceptional properties of this digital camera technology include highly authentic color images, a high light sensitivity of < 1 lux permitting high-quality inspection even under minimal lighting, as well as a resolution that has now reached 480 lines and is comparable to that of tube cameras.

Figure 2: Modern CCD cameras for underwater application

Nearly any size can be built for special applications. The smallest camera that we currently deploy to inspect steam generators has an overall height of no more than 2.6 mm including the lighting.

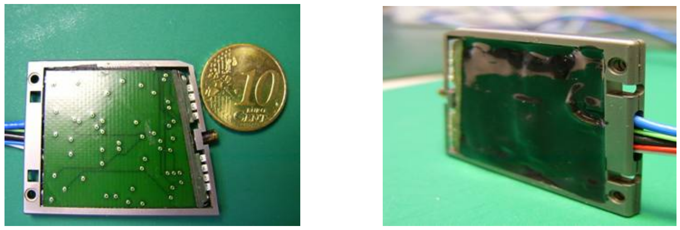


Figure 3: 2.6-mm camera for steam generator inspections (prototype)

These are supplemented by other cameras equipped with integral pan-and-tilt mechanisms and/or zoom lenses for magnification up to 72 x.

The modular design and relatively low cost of spare parts enable repairs to be carried out quickly and at low cost. Suitability for use underwater has also been significantly improved through the development of innovative seals and connectors. Finally, CCD cameras are simply less expensive than tube cameras.

Despite recent improvements, the lower radiation resistance is currently the only disadvantage compared to tube cameras:

Tube camera:	$> 2.5 \times 10^6$ rad/h	dose rate
	$> 2.5 \times 10^8$ rad	total dose
CCD camera:	no significant radiation resistance	

For this reason, tube cameras are still being used today in areas with high dose rates, such as at fuel assemblies or in the vicinity of the core shroud or core barrel.

The advent of digital camera technology also enabled inspection image processing and documentation to "go digital". Apart from the advantage of being able to process images faster, this also made it much easier to locate past video images quickly for comparison purposes. Compared to videotapes, CD ROMs and DVDs do not suffer any losses in quality during storage and also take up much less space.

To ensure that a consistently high level of quality is maintained throughout the course of a visual inspection, the system is calibrated underwater at the start and end of the inspection using a specially prepared reference block on which wires of various thicknesses, certain colors and natural material cracks have to be detected and identified.

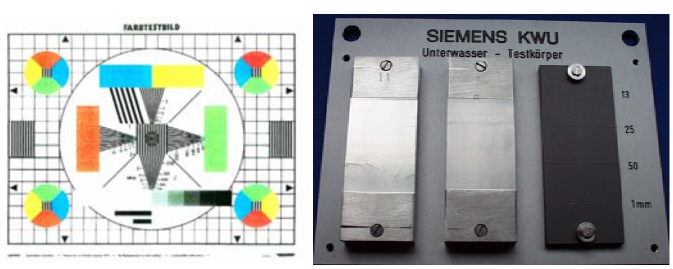


Figure 4: Test patterns and reference blocks for camera calibration

In addition, software has been developed to support "manual" image evaluation, providing objective information for specific tasks. One example is an integral sizing function. The exact size of a defect or other irregularity can be determined by comparing it against reference flaws. In future, it is planned to measure dimensions directly based on the distance from an object and the zoom factor.

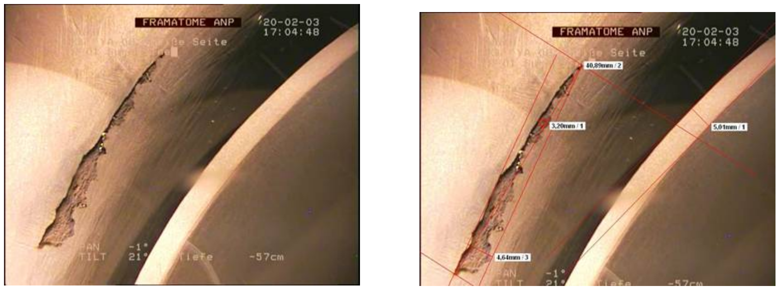


Figure 5: Image analysis: sizing of discontinuities

Further support is provided by a target mark integrated into the camera lens, enabling precise axial alignment with a target object.

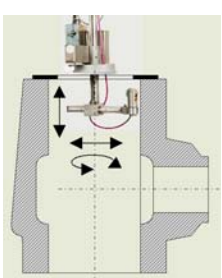
While the technology itself has been making advances, inspection personnel have also gone through appropriate training and qualification. Framatome ANP currently has an accredited test laboratory for visual inspections, and the inspection personnel are certified to DIN EN 473.

3 DEVELOPMENT OF MANIPULATOR TECHNOLOGY

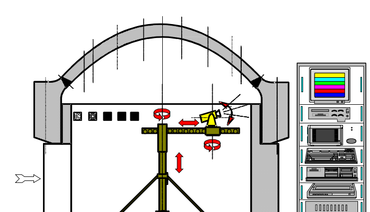
In addition to the camera systems, the associated manipulators have also been the subject of extensive development, leading to fundamental advances in this area, too.

In the old days, the cameras deployed for underwater inspections were manipulated using their own cables, thin rods and ropes attached to the top of the camera and it took a great deal of effort to bring them to their inspection locations.

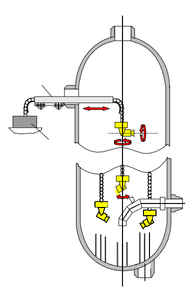
Today the cameras are accurately moved and positioned both above and below the surface of the water by state-of-the-art manipulator systems equipped with appropriate controls.



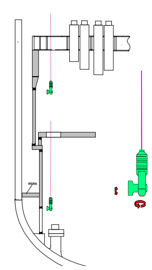
valve body inspection



RPV closure head inspection



pressurizer inspection



inspection of BWR internals

Figure 6: Examples of inspection manipulators

Position coordinates and many other items of information such as the location, date of recording and name of the power plant can all be overlaid on the video image. If the cameras have pan-and-tilt mounts, the tilt angle and degree of rotation are also displayed. All image, position and identification data are integrated into the documentation. This type of documentation guarantees reliable reproducibility and comparability with subsequent inspections for many years to come.

The next step in this course of development – specifically for underwater inspections – was to combine the camera and manipulator into a single, highly mobile and highly maneuverable, multi-task unit.

The result – born in the mid-1990s – was "SUSI", our "Submarine System for Inspections". In the years that followed, SUSI's operability and technical features were further enhanced, and it gradually became smaller and smaller for a wider range of applications.

Figure 7: Various SUSI models

The lighting system – a significant factor for any high-quality inspections – was optimized by installing a large number of small, powerful and controllable spotlights. A depth sensor permits safe travel at a certain depth or diving to a different depth, etc. SUSI 420 with a diameter of 420 mm gave rise to SUSI 270 which, in turn, led to SUSI 190 for inspecting the shell sides of steam generators as well as pressure vessel interiors.

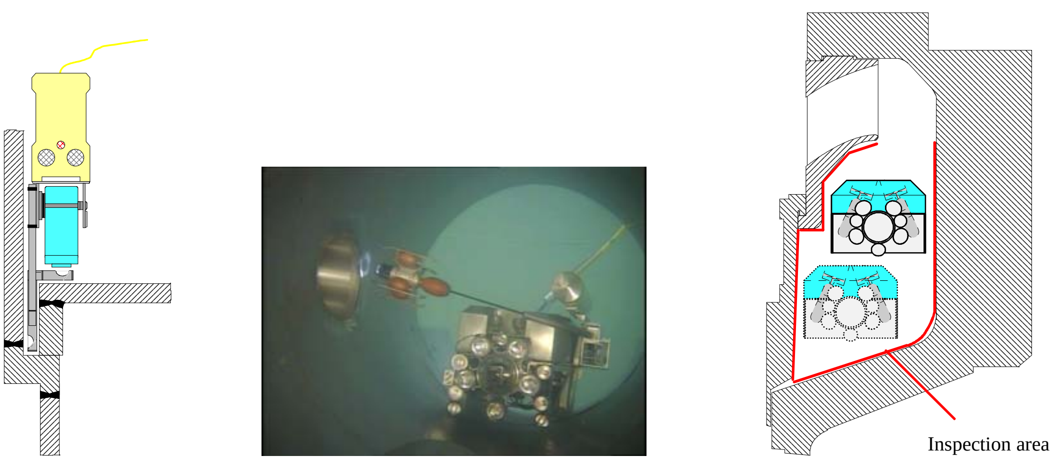
4 TECHNICAL DATA

Model / Diameter	420	270	190
Design	Modular	Modular	Modular
Weight	15 kg	8 kg	5 kg
Maximum depth	50 m	50 m	50 m
Maximum cable length	70 m	70 m	70 m
Maximum water temperature	35° C	35° C	35° C
Depth control using pressure sensor	Yes	Yes	No
Can be equipped with CCD camera	Yes	Yes	Yes
Can be equipped with tube camera	Yes	Yes	No
Equipped with rear view camera	Yes	Yes	No
Siemens controller	S7	S7	S7
Data overlay	Yes	Yes	Yes

SUSI, in its current versions, is now being deployed to inspect nearly all of the reactor coolant system components as well as pressure vessels, tanks and piping of the steam, condensate and feed water cycle of all nuclear power plants in Germany as well as those in many other countries.

Some of the areas in which SUSI is deployed include:

- Reactor pressure vessel and its internals
- Steam generator tube bundle (shell side)
- Steam generator channel head
- Reactor coolant piping
- Reactor coolant pumps (access via reactor coolant lines)
- Thermal sleeves (with the aid of special auxiliary equipment)
- Gaps (using a specially adapted miniature camera)
- Monitoring of manipulation activities, hoisting operations and core loading
- Post-refueling check of reactor core for conformance with core loading plan.



gap inspection reactor coolant piping/ thermal sleeve inspection inspection of reactor coolant pump

Figure 8: Examples of inspections using SUSI

The entire course of development in camera and manipulator technology as well as personnel qualifications have resulted in visual inspection techniques becoming recognized as fully-fledged nondestructive testing (NDT) techniques.

This is justified by the following features:

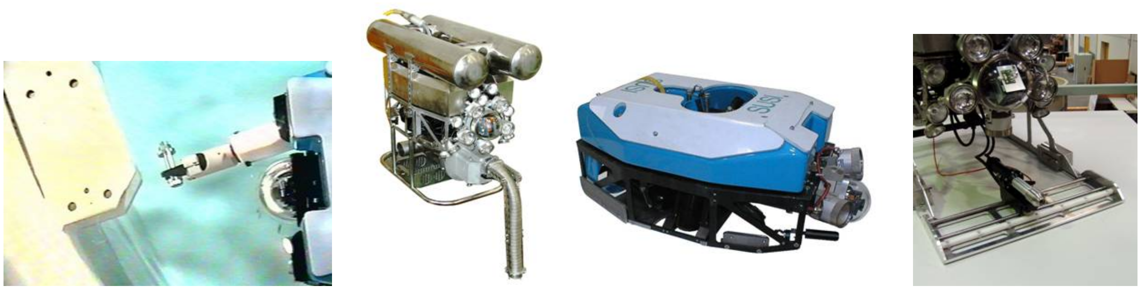
- Much higher quality of visual inspection guaranteed by certified examination personnel (accredited test laboratory)
- Adherence to codes and standards for VT (visual testing)
- Reliable interpretation of examination results
- Provision of conclusive information and assessments.

The new technologies have not only improved the quality of inspections in nuclear power plants but have also shortened inspection times quite considerably. As reactor system inspections often lie on the critical path of refueling outages, this makes a significant contribution toward shortening overall outage time.

Another advantage of the visual inspection technologies results from their extensive compatibility. The development of SUSI, in particular, was accompanied by other advances of interest for plant outage work. Some of the equipment that Framatome ANP deploys together with SUSI is:

- Grippers and vacuum cleaners for recovery of foreign objects
- Ultrasonic examination systems
- Dose rate monitors
- Satellite cameras for inspecting thermal sleeves in branch lines.

In these cases the camera is actually used to monitor the other activities being performed.



foreign object search and removal (FOSAR) dose rate measurement UT inspections

Figure 9: Examples of applications for SUSI

5 CONCLUSION

Camera and manipulator systems used in conjunction with intelligent control equipment have now reached a level enabling meaningful, reliable and reproducible results to be obtained from visual inspections. This has contributed significantly to visual inspection techniques being recognized as fully-fledged NDT methods for use in nuclear power plants.

The main benefits that these technologies give our customers is that high-quality inspections are now quicker and cost less than in the past.

Future developments will concentrate on improvements to the CCD cameras in terms of higher radiation resistance, better image resolution, and intelligent software for image evaluation and – especially for the SUSI subs – accurate position data.