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Dedicated and Standard Industrial Robots used as Force-Feedback Telemaintenance Remote Devices at the AREVA Recycling Plant

G. Piolain, F. Geffard, A. Coudray, P. Garrec, J-F. Thro and Y. Perrot

Abstract**—CEA LIST and AREVA have been developing remote operations devices, also called telerobotics for 15 years. These tools were designed for interventions in the AREVA nuclear spent fuel facilities hot cells. From these 15 years of joint research and development, several technological bricks have been industrialized and used at the AREVA La Hague facilities. This article presents some of these bricks and their industrial developments. The "TAO2000" CEA LIST telerobotics generic software controller will be first discussed. This controller has been used to teleoperate dedicated slave arms like the MT200 TAO (an evolution of the conventional wall-transmission mechanical telemanipulator (MSM) [3]) as well as industrial robotic arms like the Stäubli RX robots. Both the MT200 TAO and Stäubli RX TAO telerobotics systems provide force-feedback and are now ready to be used as telemaintenance tools at the AREVA La Hague facilities. Two recent maintenance operations using these tools will be detailed at the end of this paper.**

Index Terms**-- Force feedback, Manipulators, Radiation hardening, Telerobotics.**

I. Introduction

In the nuclear fuel cycle facilities, such as fuel manufacturing and recycling plants, nuclear power plants, interim waste storage sites, etc., materials handling must often be carried out remotely, due to the dose environment. Telerobotics and Remote Handling (RH) technologies aim at improving the operators working conditions with respect to the ALARA principle (radiological protection optimization of the workers exposed to ionizing radiation, which stands that exposure must be kept as low as reasonably achievable). These technologies also aim at providing strong reliability as well as higher safety and efficiency during the operations.

Fifteen years ago, the French Atomic Energy Agency Interactive Robotics Laboratory (CEA LIST) and AREVA started an ambitious Research and Development program in robotics and remote technologies [2]. "TAO2000", a software platform dedicated to Computer Aided Teleoperation has been developed in the framework of this cooperation [5]. New telerobotic systems have been designed and qualified to use standard industrial and dedicated robots as slave arms in the AREVA hot cells at La Hague recycling plant.

The industrial integration of these developments has been carried out by MECACHIMIE, a subsidiary of AREVA. MECACHIMIE now proposes these systems for several maintenance operations at the AREVA spent fuel management facilities in France in order to respond to the needs and requirements of the different plant life cycles.

After presenting the CEA LIST generic force feedback telerobotics software platform "TAO2000", this paper will present force-feedback telerobotic systems (based on the MT200 TAO and the radiation hardened Stäubli RX robots) qualified with respect to the nuclear fuel reprocessing facilities specifications. Then two remote maintenance applications in a high level activity area at La Hague nuclear facility using a standard Stäubli industrial manipulator will be briefly described.

II. TAO2000 Software Platform

TAO2000 is a core software platform dedicated to Computer Aided force-feedback Teleoperation (TAO is the French acronym for Computer Aided Teleoperation). TAO2000 has been developed by the CEA LIST as a generic master-slave force feedback teleoperation system able to control different types of manipulators (Cf. Fig. 1). Therefore, once the hardware I/O specificities have been dealt with, a new robot type can be integrated with the software within a few days.

A. Multi-robots, Multi-clients

The TAO2000 controller is implemented with no hard-coded limitation on the number of robots synchronously controlled (limitation only comes from computing and communication performance). This allows two kinds of cooperation between the controlled mechanisms. Firstly, two robots combined together can be controlled with a synchronous updating of all the Cartesians positions at each timestamp (this allows the control of a robot on a mobile stand). The robots can also be coupled using a virtual

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mechanism. This is how the cartesian force-feedback teleoperation is implemented.

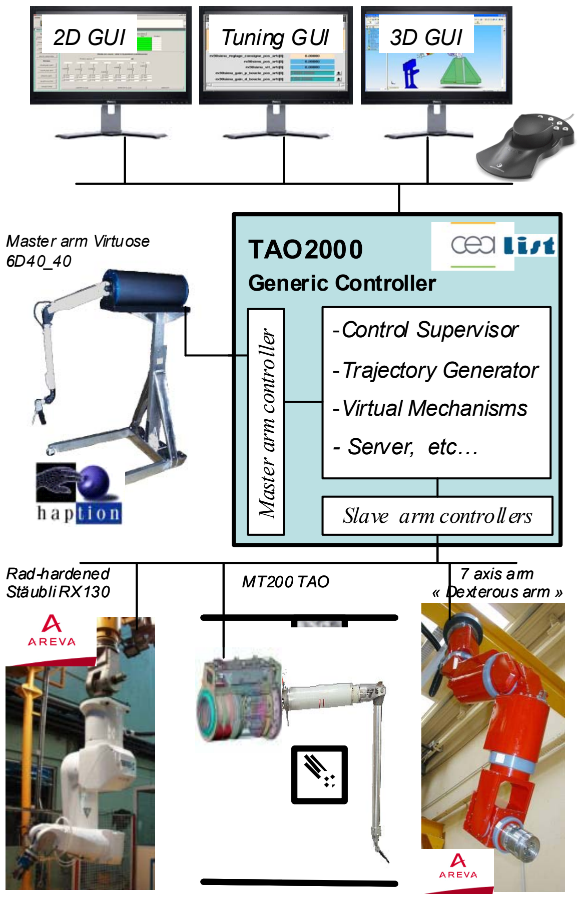

Fig. 1. TAO2000 controller software architecture

The TAO2000 controller is also multi-clients. This allows the connection of several GUI interfaces, ranging from the tuning interface, to the 3D graphical interface, as well as a SpaceMouse™. The communication between the subsystems is grounded on a client-server model where the controller is the *telerobotics server*. This model is implemented by a C/C++ library called TaoLib, also available under Python and Tcl languages.

B. *TAO2000 control modes*

TAO2000 is a multi-robots robotics and telerobotics controller software and can therefore control synchronously several robots, while providing several control modes:

- full force feedback manual mode,
- full automatic mode (position and speed control),
- shared manual/automatic mode,
- mixed position/force control mode.

The latter advanced feature uses virtual mechanism [6], hence facilitating task specification and execution by the end user. By combining all these modes, the operator may easily achieve complex tasks, such as brushing a pipe using a manipulator mounted on a mobile platform.

Control laws are implemented either in the joint space or in the Cartesian space (the operator can commute spaces during a task). Cartesian space control laws allow the force feedback coupling of different manipulators (Cf. Fig. 1).

In order to facilitate the operator manipulation some specific teleoperation features are provided:

- load compensation (66kg for one roller),
- force and position scale factor control
- observation frame modification (for easier manipulation with a camera view),
- load identification, camera's frame identification, plane's frame identification.
- …

C. *TAO2000 teleoperation control laws specifications*

Teleoperation systems will fulfil performance criteria being established by the ISO workgroup "WG 24 – Remote Handling" led by CEA LIST.

A teleoperation system is built up of an operator, a master manipulator, a bilateral connection, a slave manipulator, and an unknown environment. As all of these components must steadily work together, the TAO2000 teleoperation controller has been designed based on a passivity approach [9][10]. For example, a spring and a damper interact in the same way as the TAO2000 bilateral connection (Fig. 2).

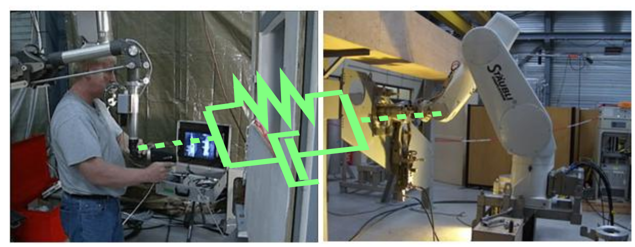

Fig. 2. TAO2000 bilateral coupling

The control system also improves the system transparency (better balance and "as is" perception) of teleoperation system. Ideal transparency is reached with a perfect transmission of the displacements and the forces between the master and the slave.

Unfortunately, manipulators (in particular industrial robots) exhibit disturbances such as joint friction, backlash, or motor cogging, at their actuator/transmission systems. These disturbances have a negative impact on the force resolution and leads to difficulties in executing well defined slow motion, and thus accurate force feedback. However, accurate joint torque control can reduce the impact of these perturbations [8]. In the case of manipulators unequipped with joint torque sensors, such as the Stäubli RX robots, an external solution has to be implemented. As a matter of fact, a rad-hard 6 axis force/torque sensor is installed at the robot's end-effector (see Fig. 3). It measures the whole wrench at the wrist thus allowing the estimation of the joint torque and improvement of the slave backdrivability. This results in improved transparency of the whole teleoperation system.

III. Dedicated and Standard Slave Robots Used at the AREVA NC Facilities with TAO2000

A. *Stäubli RX family robots rad-hardening developments*

The R&D for adapting industrial robots to remote handling requirements has been carried out by the CEA LIST based on AREVA specifications: high reliability, radiation resistance (at least up to 10 kGy), decontamination potential, radiation tolerant electronics components and sensors integration, and remote operation system with advanced functions, such as master/slave force-feedback control or robotic path planning. This approach allows AREVA to benefit from optimized investment costs (cost of an industrial robots vs cost of a specific robot), as well as high reliability and maintainability of its remote handling equipments (robustness of industrial robots).

As of today, AREVA owns a complete range of industrial robots for remote operation (RX90, RX130, RX170) which can be adapted quickly to any kind of intervention. The STAÜBLI RX robots family has been selected, thanks to their adaptability to the specifications of nuclear manipulators. They particularly provide:

- High reliability
- Water proofed, closed mechanical structure, easy to decontaminate
- Radiation tolerance up to 10 kGy integrated dose at low cost.

MECACHIMIE has integrated this new remote handling system with the assistance of the CEA LIST. The system includes the components shown in Fig. 3:

- STAÜBLI RX170 robot used as the slave arm
- 6 axes force/torque sensor (ATI Automation radiation tolerant version),
- radiation tolerant high speed signal multiplexer which replaces the stiff and large robot's umbilical,
- force-feedback control system dedicated to Computer Aided Teleoperation,
- MA23 (back-drivable) force-controlled master arm

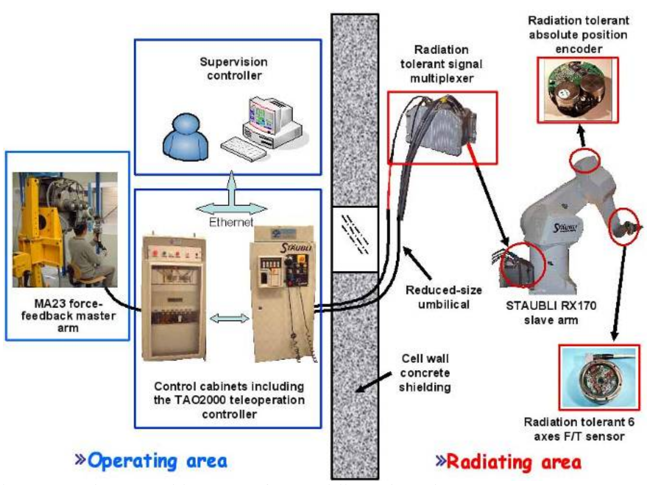

Fig. 3. Hardware architecture of a Stäubli RX based AREVA CAT system

The 6 axes F/T sensor necessary to force-feedback control is mounted between the robot end-effector and the pneumatic gripper. The electronic multiplexer is integrated at the base of the robot and multiplexes all the data signals of the robot's internal sensors, F/T sensor and the gripper. The system connection is therefore achievable with only two small electrical plugs (standard plugs used in nuclear facilities) going through the engineered penetrations (36 mm diameter) in the cell walls.

The performances obtained using STAÜBLI RX robots in remote operations with force-feedback have been validated, allowing safe remote high precision tasks with payloads far heavier than those encountered in manufacturing robotic applications. For example, it has been found by MECACHIMIE that a payload up to 100daN can be handled by a STAÜBLI RX170 robot in some conditions. Therefore the performance obtained in robotic mode has been validated and can be compared with the performance obtained with the standard STAUBLI controller.

B. *MT200 TAO : a wall-transmission manipulator adaptation*

The MT200 La Calhène® is an existing wall-transmission mechanical telemanipulator that can be disconnected from the cold side.

The MT200 TAO system is the result of the cooperation between the Interactive Robotics Unit of CEA LIST and AREVA. A detailed description of this system could be found in reference [3]. The MT200 TAO was designed to address the following specifications:

- guarantee same or better performances as the original MT200 telemanipulator,
- increase working volume allowing ceiling access,
- improve workstation ergonomics of the existing MT200 telemanipulator,
- allow the operator to move away from the controlled zone in certain workstations potentially exposed to contamination or high radiation rate
- ensure safety for difficult tasks and reduce operator fatigue when located within the control zone
- allow playback of some repetitive tasks that do not require force feedback (robotic mode)

The MT200 TAO system functionally replaces the mechanical master arm. The wall transmission and the slave arm are those of the MT200 La Calhène®, the design originating from the early 80's. The slave drive unit can be fitted to any La Calhène® wall transmission model in less than an hour and therefore to any telescopic slave arm produced by this constructor. The compact force-feedback master arm is a Virtuose 6D/4040 constructed by Haption® on a CEA LIST patented design using ball screws. It can exert a permanent effort of approximately 40 N.

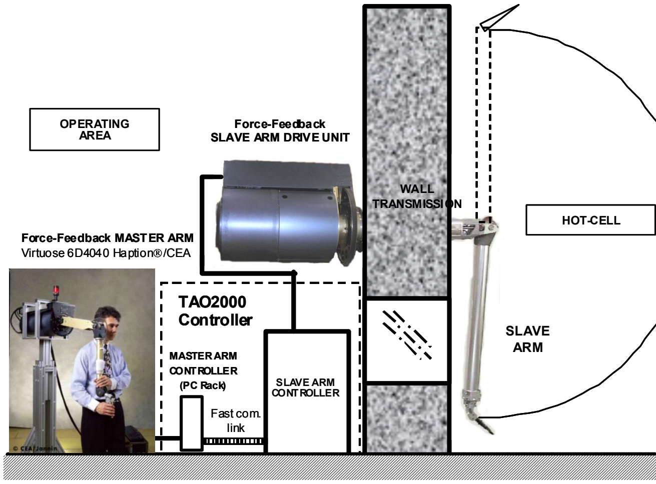

Fig. 4. Hardware architecture of a MT200 TAO based AREVA CAT system

IV. TELEMAINTENANCE OPERATIONS AT THE AREVA LA HAGUE FACILITY

The purpose of these maintenance operations were to remove the rollers of the nuclear fuel dissolver wheel and to clean the inter bucket spaces of the wheel of the dissolver. At the La Hague nuclear plant, there are 3 similar dissolution cells.

The first operation has already been carried out successfully in two dissolution cells (first detailed in [4]), and the second operation has been recently validated on a mock-up.

A. Context description

The shearing and dissolution process is shown on Fig. 5. Fuel is cut into rods of approximately 35mm long. These "hulls" contain the used fuel nuclear material. They fall by gravity in one bucket of the dissolver wheel, where nuclear material is dissolved by hot nitric acid.

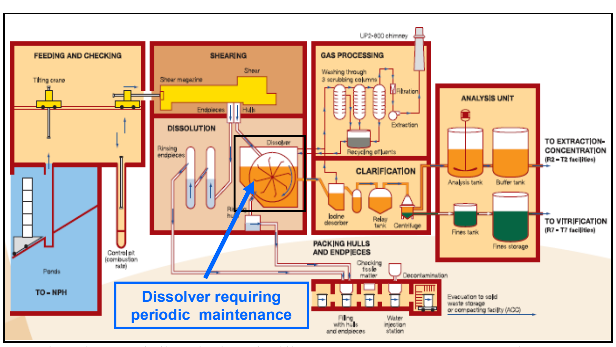

Fig. 5. Shearing and dissolution facility at AREVA La Hague plant.

The dissolver is located in the dissolution cell shown in Fig. 6. It is composed of a flat tank filled with hot concentrated nitric acid and a 12 buckets dissolution wheel. Periodically, the wheel of the dissolver is raised up with its cover in the high activity maintenance cell located above the dissolution cell.

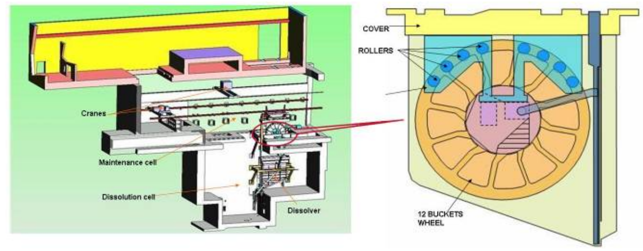

Fig. 6. CAD model of the dissolution cell and wheel.

B. Changing the rollers

The wheel of the dissolver rolls on eight rollers fixed to a supporting frame. The rollers must be replaced every 7 years within the framework of preventive maintenance.

The roller is composed of a rolling part and of a fixed part. Each roller is locked by a key which jams the roller to the supporting frame. Unlocking is carried out by a special tool. The key, the special unlocking tool and the roller are equipped with specific handles to be gripped by the manipulator. The roller, key and unlocking tool weights are respectively: 66daN, 36daN and 56daN (Cf. Fig. 7). The centre of gravity of the roller is located at 170mm of the gripping handle. All in all, this maintenance operation needs a powerful remote handling device.

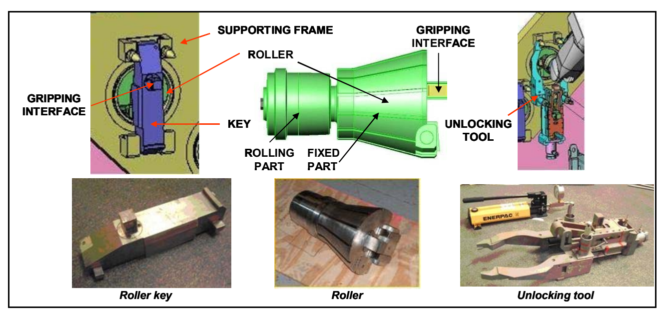

Fig. 7. Principal mechanical tools and roller parts.

The maintenance cell is equipped with wall-mounted MT200 mechanical master-slave manipulators. Unfortunately, these manipulators don't have the payload capacity required for these operations. Therefore, new remote handling equipments had to be introduced inside the cell at a competitive cost.

The selected CAT system is based on the Stäubli RX170 robot like the one presented below (see §III. A. and Fig. 2), except that, for the rollers changing operation, MECACHIMIE modified the inverters capacities in order to exceed RX170's nominal payload.

Almost all TAO2000 control modes have been used successively during this operation (more details can be found in [4]):

- predefined trajectory to drop off the rollers and the tools,
- cartesian force-feedback teleoperation mode for unlocking and to extract the roller,
- Mixed position/force mode during the hole cleaning (see Fig. 8).

The whole operation, for one hot cell, including the CAT system settling and removing, and the changing of eight rollers, took 10 days (operating 10 hour days).

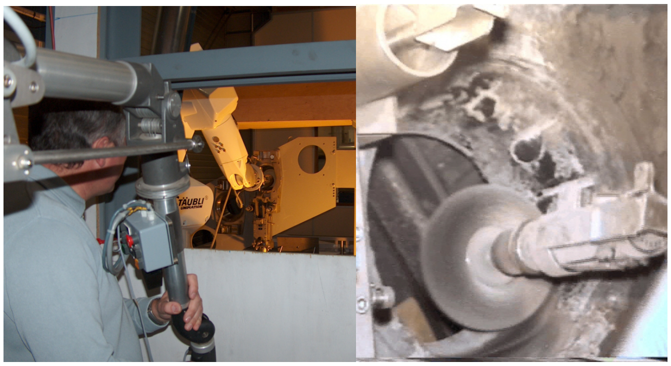

Fig. 8. Brushing task on the mock up (left) and in the hot cell (right).

C. The cleaning of the inter bucket space

The wheel is composed of 12 buckets connected two-two by a balance weight (Fig. 9). The buckets are comparable to sieves where the various faces are constituted by perforated plates. The holes diameter of the perforated plates is within the millimeter range.

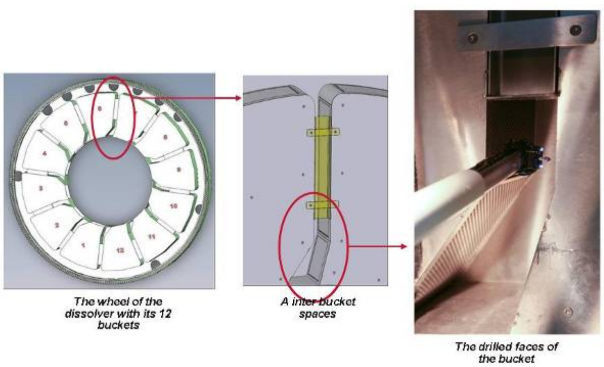

Fig. 9. The inter bucket spaces

The maintenance operation consists in cleaning the inter buckets spaces using a high pressure water jet. The purpose of this cleaning is to remove the deposit which could lead to clogging. Access to the inter buckets spaces by HP hose is made particularly difficult due to the balance weights.

This operation requires an accurate automatic system which guarantees that every hole is reached by high pressure water jet, and which minimize the volume of generated effluents.

Thanks to the success of the previous maintenance operations (§IV. B.) AREVA has decided to use the same equipment for the new cleaning operation of the interbucket space .

The Staübli RX170 based CAT system was thus selected for this second maintenance operation, for which the different phases are:

- access to the inter buckets spaces and contact detection,
- identification of the plans equation,
- cleaning of the inter buckets spaces using a high pressure water jet,
- cleaning check and quality control.

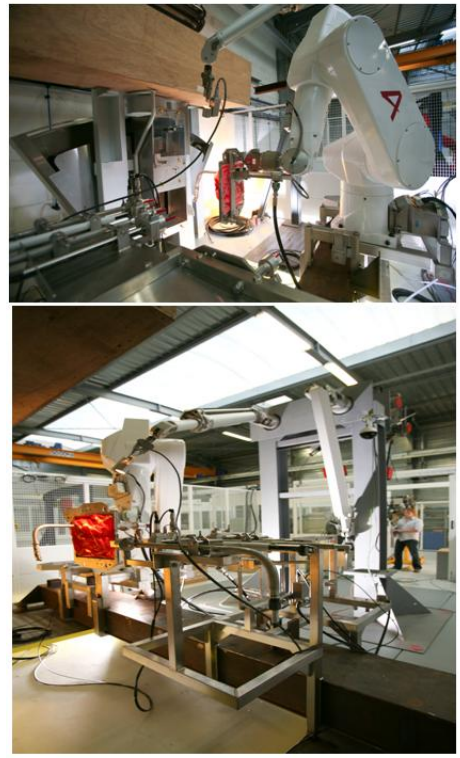

Fig. 10. Tool rack with several tools and the wheel mock up.

Tool choice and approach operations are performed using the force feedback remote operation feature of the system. All cleaning operations with the high pressure water are achieved with automatics trajectories in order to insure the passage above every holes of inter bucket with a constant rate and relative position, and also in order to optimize the volume of generated effluents.

Considering the geometrical complexity of the bucket and the balance weights, every inter bucket is divided in several plans. Every plan is the object of a specific automated cycle.
The preparation of this intervention was realized and qualified at the end of 2008. The intervention initially foreseen in 2009 is today planned for the end of 2010, due to the plant operation schedule

V. Conclusions and Perspectives

Remote Robotics, the combination of Robotics and Remote operation, applied in the nuclear industry is an instrument of continuous progress and sustainable development:

- Reduced dose to the operator by putting distance with the work zone.
- Minimization of the volume of waste inferred by the safety of the operations and the reliability of the intervention system
- Risks mitigation due to force feedback remote operation and the automation of complex or repetitive tasks,
- Robot versatility for "multi-purpose" applications - A reality today: a robot is cheaper than a special multi-axis machine
- Evolution of operators tasks by allowing them to work in a remote comfortable environment.

As all the qualification tests have already successfully been realized; the first maintenance operation using a MT200 TAO in a hot cell at the AREVA La Hague facility is scheduled during 2010.

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VII. Biographies

Gérard Piolain was born in Saint-Lo, France, on June 3 1958. Gérard PIOLAIN is a 1981 graduate from Ecole Nationale Supérieure des Arts et Métiers and holds a Master of Engineering.

He joined AREVA NC la Hague in 1982. He acted as operation engineer and was in charge of the maintenance team at the new UP3 plant.

Since 1991, he has worked as development project manager in Technological Department of AREVA NC/La Hague in the Teleoperation and Robotics department. In 2003, he was given Expert status at AREVA.

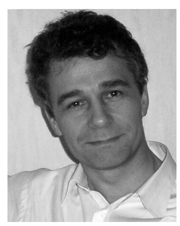
Gerard is involved in an ambitious Research and Development program in robotics and remote technologies aiming to cover the requirements of different plant life cycles. He improved the new remote manipulators in partnership with the Robotics Service of CEA, such as the force-feedback teleoperation of industrial robots, the wall-transmission telescopic mechanical telemanipulator called MT200 TAO and the Long Range Inspection Carrier called LORA. During this period of time, he was the prime contractor for telerobotic operations such as the repair the tightness defect on the acid rinser of T1 facility with an industrial robot and the remote replacement of 8 roolers of the dissolver wheel.

Franck Geffard (PhD) was born in France, on January 22, 1972. He holds a Master of Engineering degree from the Ecole Centrale de Nantes, and received his PhD degree in Applied Control and Computer science from the University of Nantes, France.

Since 2001, he has been working at CEA LIST (French Atomic Commission Center), in the Interactive Robotic Units, as a Research Engineer. During his first five years in the laboratory, he led the TAO2000 (Robotic and Force Feedback Telerobotic Controller) development team. His main areas of interest include modeling and real-time control of complex systems, Telerobotics and Cobotics.

He was involved in the TAO2000 controller transfer to MECACHIMIE for the industrialization of the Stäubli RX170 based CAT system, and in the MT200 TAO controller development.

Alain Coudray was born at Paris in France, on February 3, 1968. He is a 1991 graduate from Ecole Centrale de NANTES and holds a Master of Enegineering,. From 1993 to 1997, he worked as a development and qualifying testing engineer at SGN (AREVA Group) robotic department at Beaumont la Hague. In 1997, he joined the SGN mechanical engineering service at Equeurdreville as a design engineer. In 1999, he joined MECACHIMIE (AREVA Group) as a project manager and a robotic development engineer. Since 2001, he has been managing projects related to the development of robotic and remote handling systems for use in exceptional operation, maintenance, dismantling or decontamination of nuclear installations. These developments are mainly carried out from the industrialization of systems designed for AREVA by the CEA robotic department. In 2004, he has created the MECACHIMIE robotic service and became an Expert of the AREVA Group. Since 2007, he is responsible for the robotics activity of MECACHIMIE.



Philippe Garrec is a senior researcher and a consultant at CEA LIST that he joined in 1985. He received is engineering degree at the Ecole Nationale Supérieure d'Arts et Métiers in 1983. He briefly worked as an engineer at the Direction of R&D from Electricité de France (EDF), then as a scientific staff for CEA, Direction des Applications Militaires during is duty service in 1985. He has been since consistently working on robotic research and development, in particular on electric actuators and energy recovery, telescopic structures and transmissions, a robot leg for hexapod and various manipulators. Among others, he led an international project in which the first demonstration of a full-size hexapod transporter robot was made in real power nuclear plants (1994). He is also credited of the invention of the screw-cable actuator that he initially developed for the master-arm Virtuose 6D4040 intended for teleoperation (2001). Upon this actuator, he led the design of the upper limb exoskeleton ABLE and is currently involved in the design of low limb exoskeleton as well. He is also the designer of two master-slave computer-assisted teleoperators for the nuclear industry - CEA DEN and AREVA NC La Hague reprocessing plant - and the principal designer of a giant telescopic manipulator for the defense project Laser Mega-Joule (CEA LIST-CYBERNETIX collaboration). Since 2004, he has been involved in the modeling and identification of friction and transparency in mechanisms or transmissions. He is presently working at a computer program for simulation purpose and developing force observation methods for control. He has been involved in international standardization activity within International Standard Organization (ISO) since 2004. In 2009, he was nominated as convener of the newly formed ISO/TC85/SC2/Working Group 24 (Remote handling devices for nuclear applications) and is promoting a new standard for telerobotics. He has written 21 articles of conference and journal (15 as first author and 6 as co-author), 3 book contributions and is the author of 15 delivered patents and 5 filed patents.