Force-feedback teleoperation of an industrial robot in a nuclear spent fuel reprocessing plant

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Abstract

Purpose – Aims to make an industrial robot work as a telemanipulator with force feedback, in order to carry out various tasks for remote handling in nuclear fuel cycle plants.

Design/methodology/approach – The robot STAÜBLI RX170 (used as a slave arm) has been fitted with a force-torque sensor and an electronic system for sensors’ signals multiplexing. The overall system has been made tolerant to γ radiation up to a 10kGy integrated dose. The industrial robot has been coupled to a master arm with force feedback capability and to the Computer Assisted Teleoperation controller TAO2000 developed by CEA-LIST.

Findings – The result of the maintenance operation reported in the article, carried out with a Staübli RX170 robot at AREVA/COGEMA La Hague plant, illustrates this validity of the approach and demonstrates how remote handling can beneficie of this new technology.

Originality/value – Introduce the teleoperation of industrial robots as a new solution for the maintenance of nuclear facilities. Wrist force/torque sensing and advanced master-slave controller provide the operators with a high performance teleoperation system. Only limited modification of the existing design of the industrial robot has been carried out in order to transform it into a nuclear telemanipulator.

Keywords Robotics, teleoperation, force-feedback control, radiation tolerant electronics.

Paper Type Application paper.

Introduction

In the facilities of the end of the nuclear fuel cycle, like spent fuel storage pools, reprocessing plants, Plutonium-based fuel manufacturing plants or waste temporary storage units, materials handling must be carried out remotely, taking into account the nuclear highly radiating environment. In addition to the automation requirement, robotics equipments in the nuclear industry must be substituted to human operators in order to respect the ALARA principle (radiological protection optimization of the workers exposed to ionising radiation, which stands that exposure must be kept as low as reasonably achievable). More over, remote handling technologies aim to improve the working conditions, as well as the quality, of the work achieved by the operators.

Ten years ago, COGEMA (AREVA Group) and CEA-LIST (French Atomic Energy Commission) launched an ambitious R&D program in robotics and remote handling technologies applied to spent fuel management facilities, with the aim to cover the requirements of the different plant life cycle steps [1].

In nuclear fuel reprocessing facilities, remote handling equipments have to deal with severe constraints:

- maximum integrated dose for one year between $10^4$ and $10^5$ Gy,
- decontamination capability using potentially aggressive products,
- operation at high temperature (50°C),
- electromagnetic compatibility,
- volume and weight compatible with remote operations,
- compliance with safety and quality standards,
- diagnosis and maintainability constraints,
- compatibility with waste management.

This article focuses on one of these developments which consist in the adaptation of an industrial robot to the constraints listed here above. That includes the development of radiation tolerant electronic parts, force-feedback control software for master-slave teleoperation, and the integration of the overall technologies in order to build a remote handling system. The application of these developments to the maintenance of a dissolver is also reported. The purpose of this operation is to change the rollers of a big wheel which is located in a high level activity area of the AREVA/COGEMA facility at La Hague (France). This recurrent operation has been carried out in November 2005 with the system presented in this article [2].
Design of the new remote handling system

The R&D for adapting industrial robots to remote handling requirements has been carried out by CEA-LIST based on the specifications of COGEMA: to be highly reliable, to withstand radiation (at least up to $10^4$ Gy), to be decontaminable, to integrate radiation tolerant electronics components and sensors, and to provide the teleoperation system with advanced functions, such as master/slave force-feedback control or robotic path planning, for example [3,4]. This approach allows in fine COGEMA to benefit of reduced investment costs (industrial robots are cheap), as well as of high reliability and maintainability of its remote handling equipments (industrial robots are robust).

Today, COGEMA owns a complete range of industrial robots for teleoperation (RX90, RX130, RX170) which can be adapted quickly to any kind of intervention. The STÄUBLI RX robots family has been selected, because these robots can be adapted to the specifications of nuclear manipulators, and particularly they provide:

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

MECACHIMIE (a subsidiary of AREVA/COGEMA) has integrated this new remote handling system for the dissolver maintenance with the assistance of CEA-LIST. The system includes the components shown in figure (1):

- a STÄUBLI RX170 robot used as the slave arm
- a 6 axes force/torque sensor from ATI Automation (radiation tolerant version) [5],
- a radiation tolerant high speed signal multiplexer which replaces the stiff and large robot’s ombilical,
- a force-feedback control system dedicated to Computer Aided Teleoperation,
- a MA23 (back-drivable) force-controlled master arm

Figure 1 Design of the STÄUBLI RX170 based remote handling system

The performance obtained using STÄUBLI RX robots in teleoperation with force-feedback has been validated, allowing to safely carry out high precision tasks remotely and to handle payloads which are far heavier than those encountered in manufacturing robotic applications [6,7]. For example, it has been found by MECACHIMIE that a payload of up to 100 daN can be handled by a STÄUBLI RX170 robot in certain conditions.

TAO2000 controller

TAO2000 is a core software multi-client and multi-robot dedicated to Computer Aided Tele-operation (actually, TAO is the French acronym for CAT). TAO2000 has been
developed formerly by CEA-LIST as a generic master-slave teleoperation controller able to control any types of master or slave manipulators [8,9]. MECACHIMIE has used this core software to integrate the MA23/RX170 telerobotic system used for the maintenance of the dissolver.

The TAO2000 system provides a wide set of features, which may be divided into three main parts: the real-time controller, the tuning and maintenance interfaces, and the 3D Graphical User Interface (figure 2). TAO 2000 provides different control modes, ranging from full manual force-feedback control to shared manual/automatic and mixed force/position control. These advanced features use the virtual mechanism concept, which eases the user task specification [10]. TAO 2000 is a multi-robot controller, which means that one may connect a master arm with several slave arms and switch from one slave to another at will. The client API is available either as a C library or as a robotic programming language based on Python generic interpreted language [11].

The aim of a CAT system is to decrease the hardness of the operators work (by means of tool weight suppression, automatic control modes, etc.) in order to increase the quality and the safety of remote handling operations. For example, using a prismatic virtual mechanism to drill a hole insures that the drill always keeps its axis. The hole is then well made and the risk of breaking the drill is limited. Such systems have been developed for years by CEA-LIST for use in nuclear environments [12].

TAO2000 controller brings innovative functionalities for teleoperation such as:

- passive cartesian force-feedback master-slave control
- perfect balancing of the master and slave arms
- accurate monitoring of the forces applied by the slave arm to its environment
- tool weight balancing
- independently adjustable velocity and force homothetic ratio in master/slave control mode
- assistance to operators tasks by means of virtual mechanisms
- automatic pursuit of the gripper by a supervision camera

Associating joint and cartesian control laws with a trajectory generator and a virtual mechanism simulator, the TAO2000 controller provides also the following control features:

- joint position control with trajectory generation
- joint velocity control
- cartesian position control with linear, circular or polynomial trajectory generation
- cartesian velocity control
- passive cartesian force/position control via virtual mechanism specification
- passive cartesian force-feedback shared master-slave/automatic control via virtual mechanism specification

The cartesian control laws currently implemented in TAO2000, rely on a bilateral master-slave controller (figure 3). The transparency of the system is insured with a torque loop using either joint torque measurement, or wrist force/torque measurement. The cartesian position control uses the transpose jacobian matrix. Combining all these features, the operator may achieve complex tasks, like drilling, tapping, brushing, etc, with less effort and better productivity and quality [7].

Portability and genericity are two aims of the software design. Though most of its parts are reusable components, TAO2000 is an end-user oriented system, with a well-defined set of features, including control and GUI capabilities. It is highly configurable and a new robot can be integrated in a few days, once hardware I/O problems have been dealt with. Combinations of already integrated robots can be built for a specific application by just modifying some configuration files. These capabilities have been demonstrated by integrating the controller on a large variety of telerobots [3].
Application to a maintenance operation in a reprocessing plant

Operations in a reprocessing plant consist of using chemical and mechanical processes to separate recyclable materials from the spent fuel used in nuclear power plants. Spent fuel casks received at the COGEMA La Hague plant are unloaded remotely under either dry or wet operating conditions. The spent fuel assemblies are transferred to baskets for interim storage in spent fuel pools for a minimum of 2 years to allow for cooling. Then reprocessing begins. The fuel assemblies are removed from the pool and sheared into 2-3 centimeter pieces. The nuclear material in the fuel is dissolved in an acidic solution. Then the uranium, plutonium and fission products are separated using solvents and recycled into new fuel elements. The waste undergoes special processing for final disposal.

The process of the shearing and dissolution facility is shown on figure (4). Fuel is cut into lengths of approximately 35 mm. These “hulls” contain the nuclear matter. Gravity makes them fall into a dissolution wheel. Dissolution is one of the most important steps in this process which requires an equipment called the “dissolver”. The dissolver is part of the dissolution cell shown in figure (5). It comprises a specific tank filled with boiling concentrated nitric acid and a 12-scoop 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.

The maintenance cell is equipped with wall-mounted MT200 mechanical temanipulators (figure 6); with a 500 daN hook crane and with another crane equipped with a heavy duty manipulator normally devoted to the maintenance of the wheel.

Unfortunately, this manipulator is now obsolete and its maintenance would be too expensive. For that reason, and because the MT200 telem manipulators don’t have the payload capacity required for this operation, a new remote handling equipment should be introduced inside the cell at low cost.

Dissolver maintenance operation

The wheel of the dissolver rolls on eight rollers fixed to a supporting frame attached under the dissolver cover. For changing these rollers, the whole equipment is supported by a rolling beam in the maintenance cell (figure 5).
Figure 6 MT200 mechanical telemanipulators

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 (figure 7). The roller, key and unlocking tool weights are respectively of: 66 daN, 36 daN and 56 daN. The centre of gravity of the roller is located at 170 mm of the gripping handle. The maximum robot payload, including the gripper and the force/torque sensor, is 80 daN.

The procedure for changing a roller is the following:
- install the “unlocking tool” on the supporting frame,
- Connect the feeding pipes to the unlocking tool
- Unlock the key
- Take the key out
- Take the unlocking tool out
- Pull the roller out (pulling force may be up to 200 daN)
- Clean the roller housing with a rotative brush
- Put in place a new roller
- Install the “unlocking tool” on the supporting frame,
- Connect the feeding pipes to the unlocking tool (pneumatic power)
- Put in place the key
- Lock the roller by means of the unlocking tool
- Take the unlocking tool out

All these operations must be carried out for each of the eight rollers. Additional secondary operations must be carried out in order to make possible the roller changing. That is the introduction and mounting of the telerobotic equipments, the installation of a rack containing the rollers (new ones and old ones), the handling of the different tools, etc.

Operation feedback

The preparation of the intervention started six months before the beginning of the operation in order to integrate and test all the parts of the system. For that purpose, a one-scale muck-up representative of the upper part of the wheel with its eight rollers has been developed. This muck-up allowed verifying that the RX170 teleoperated robot was able to handle all the mechanical parts and tools necessary for the operation. It has been verified that the robot was able to achieve successfully all the tasks listed here above. Most of these tasks has been carried out in teleoperation without specific assistance, except two of them: the brushing of rollers’ housings for which a virtual mechanism, maintaining the orientation of the brush along the axis of the rollers was used; and the transfer of the key’s locking tool between the tool rack and the wheel, which was carried out by the robot with the help of a programmed
trajectory. Nevertheless, some unexpected tunings of the robot’s power amplifiers were necessary in order to make the robot carry the heavy rollers...

The location of the robot, as well as the mechanical supports for tools and rollers, with respect to the wheel was a critical point to assess, because the free space between the wheel and the robot’s supporting beam was very limited (figure 8). Finally, the wheel muck-up has been used for training the operators who adopted this new remote handling system after a couple of days with an amazing easiness (figure 9). This was certainly a very good sign for the success of the future operation!

By the end of November 2005, the operators got the wheel out of the dissolver and raised it in the maintenance cell. Then, using the RX170 robot as a telemanipulator, they took out one by one the keys locking the rollers and replaced them by the new ones. A rotative brush has been used for cleaning the housings of the rollers inside the wheel (figure 10). But, due to an unforeseen error in the model of the wheel’s handling device, the automatic trajectory programmed couldn’t be used and the operators chosen to move manually the key’s locking tool. The total duration of the operation didn’t exceed two weeks, compared to several couple of weeks which were necessary formerly when the operation was carried out using conventional remote handling equipments without force-feedback.

Force-feedback master/slave teleoperation, in combination with advanced force control, allowed being flexible and the operation was never stopped nor delayed because of the robot. That wouldn’t certainly be the case if the tasks would have been programmed in advance. More over, the quality of the operation has been found very well.

At the end of the operation, the RX170 robot has been disconnected and stored in another cell nearby the dissolution cell. COGEMA plans to use it again in order to carry out other maintenance operations, for example to clean the dissolver wheel with high pressure water.

**Conclusion**

Providing better security and safety conditions, the teleoperation of STAUBLI RX robots allows the operators of COGEMA to carry out maintenance and repair interventions in active cells more rapidly and more easily. In addition to the generalized master-slave control in the cartesian space necessary to interventions in active cells, the key points of this development are: the compensation of the robot’s articular frictions (which lower dramatically the sensitivity of telemanipulation systems) thanks to force/torque control; the robustness of the TAO2000 software which has been integrated into the COGEMA controller without any rewriting of the software core; the
electronics multiplexer of the robot’s sensor signals, which makes the robot compliant with the constraints of the process, without modifying its performances.

The main advantages of the STAUBLI RX CAT system, compared to former solutions based on specific nuclear manipulators, are: reliability; flexibility; quicker and safer; reduced risks for projects; and finally lower costs. This tool is very versatile and can be used in teleoperation mode, but also in robotic mode to perform automatic tasks (like soldering or process control). More over the teleoperation functionality can be used in order to facilitate the programming of the robot’s tasks (for instance, to learn the points of a trajectory using the master arm).

The result of the robotic program carried out by COGEMA and CEA-LIST should be very valuable for the introduction of new remote handling technologies in the nuclear industry. Innovative products and sub-systems can be integrated now in a large range of remote handling systems, thus optimizing the tools provided to the operators and improving the productivity and the security of maintenance, repair and modification operations in nuclear fuel reprocessing plants.

References


**Figure 10** Maintenance of the dissolver wheel in progress:

(a) operator using the MA23/RX170 remote handling system, (b) supervisory control station, (c) taking the roller’s key out, (d) RX170 robot before introduction into the cell, (e) brushing the roller’s housing, (f) insertion of a new roller.