FUSION TECHNOLOGY

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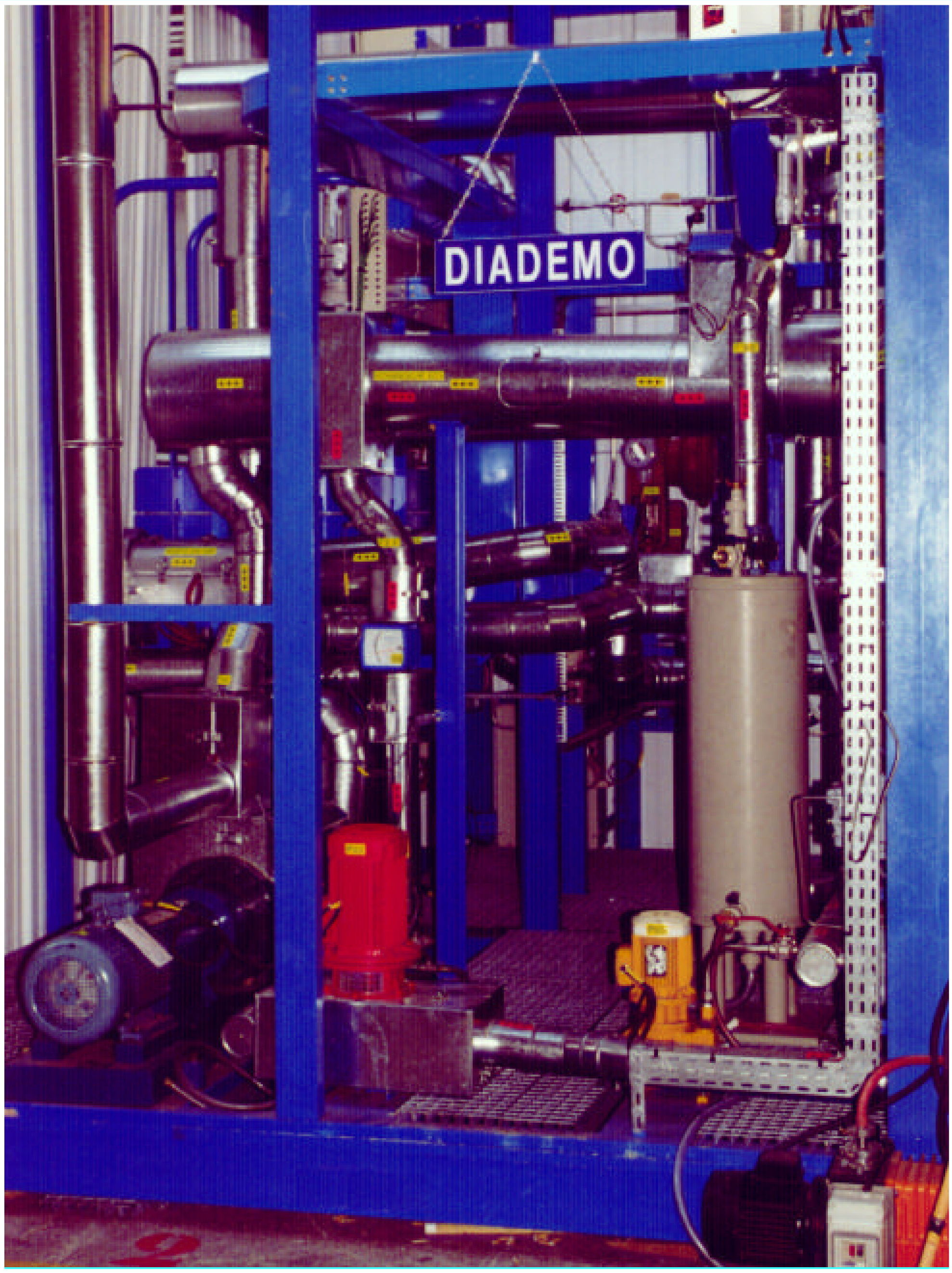

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T252

Task Title : RADIATION TOLERANCE ASSESSMENT OF STANDARD COMPONENTS FOR REMOTE HANDLING AND PROCESS INSTRUMENTATION

INTRODUCTION

This present report is corresponding to the intermediate report on CEA/DEIN/SLA and CEA/DEIN/SPE contribution to ITER T252 task "Radiation tolerance Assessment of standard components for remote handling and process instrumentation".

From now, the known missions for remote handling modules are organised around three main topics :

- very short visual in-vessel inspection (few hours) just after shut-down of experimental reactor where total dose level expected for vision modules is around 1MGy,

- extensive in-vessel inspection (few days) where total dose expected during such missions is up to 10MGy,

- maintenance (2 or 3 months) where total dose could reach up to 100MGy. The main actions to be taken during this time are the replacement of divertor cassette and the control of the blanket. It should be possible to change critical modules every week in order to not exceed 10MGy for them.

One topic should normally be added, the six-months storage of inspection modules. But, if the environmental conditions of the third ones are agreed by ITER teams (between 50°C and 200°C for a dose rate averaged to 30kGy/h), it seems not to be the same for storage period. Total dose and dose rate are unknown. Neutrons are at least 10^{12}n/m^2/s and spectrum is not defined. For all duration of post-EDA T252, we do not take into account this topic.

The purpose of CEA/DEIN is to assess the radiation tolerance of commercial electronic or optical components able to be integrated in remote handling modules. For electronic components, studies are mostly focused on MOS technologies but nothing stands to look at emerging or oldest technologies to design a digital elementary module of ITER remote control.

State of the art of methods to reduce constraints on umbilical (size, weight, maintenance) has started with delay due to the priority given to organise experiments.

1998 ACTIVITIES

ELECTRONIC COMPONENTS

The purpose of the work performed here is to assess the radiation tolerance of electronic commercial components and technologies, mainly MOS.

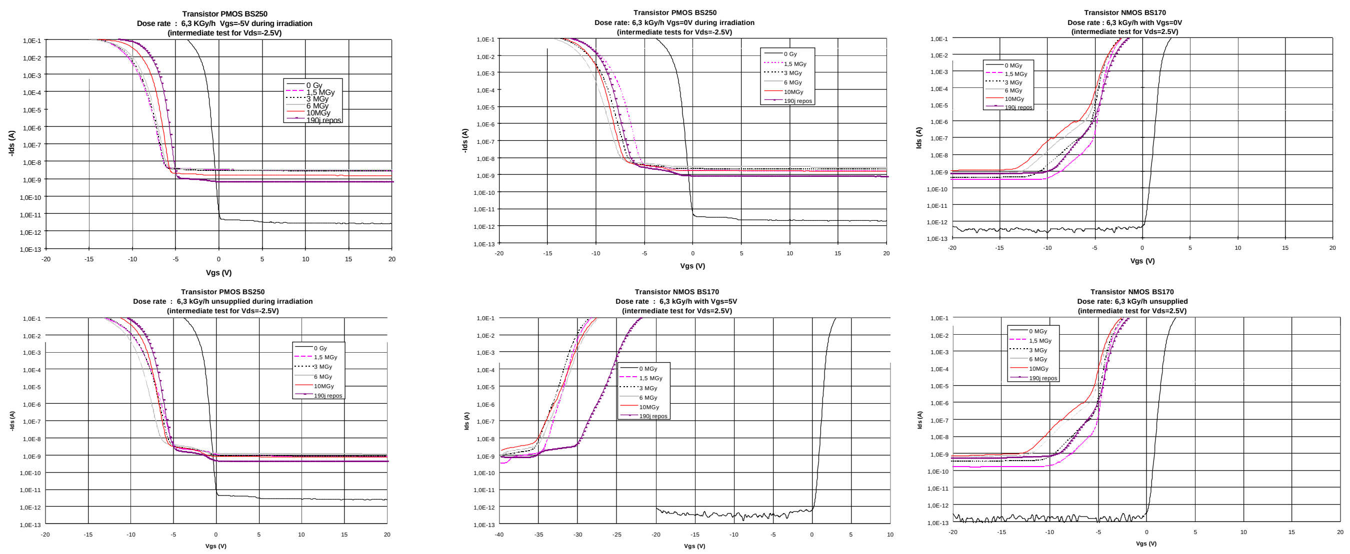


Figure 1 : Evaluation of Vgs threshold up to 10MGy of BS250 PMOS and BS170 NMOS low power transistor under different bias conditions. Tests have been made off-line.

Our strategy would also include assessments of modules (based on these components) prototyped in our lab and already industrialised able to be included in ITER engines. A first campaign of irradiation has been engaged at the beginning of the year to reach 10MGy (6kGy/h and 50°C for environmental conditions) on sets of components usually found in electronic embedded systems for lower dose tolerance.

Due to the proximity of irradiation facilities and the great number of components (for each one, at least two samples of the same lot, and when possible, multiple lots and manufacturers, multiple bias conditions to cover main future uses), intermediate tests in our lab have been scheduled at regular total dose levels. Components are pull out irradiation cells, measured and put back to be irradiated again. Figure 2 shows on the cards used for these experiments.

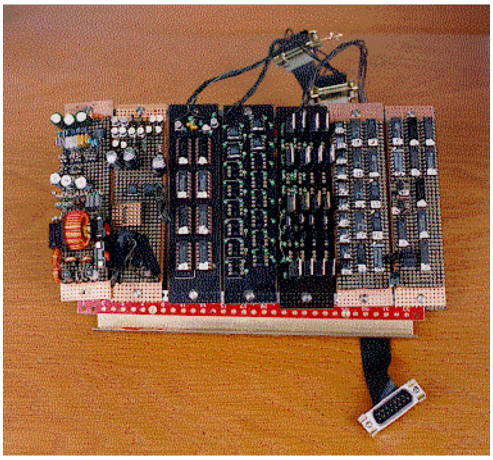


Figure 2 : Card used to irradiate set of components up to 10MGy (steps by steps tests)

Data exploitation is not yet finished but some results are shown above.

A large set of components have been irradiated with different bias conditions and evaluation has been made by steps. All the results are not yet analysed. However, the following curves (Figure 1) on PMOS and NMOS transistors give enough information to continue to test them under hardest conditions like for ITER. Permanent state has been arriving around 100kGy with no significant evolution after. Recovery at room temperature after more than 6 months is not so significant.

Curves not shown in this report give the behaviour of transistors from other technologies. Like for MOS components, a permanent state is reached for bipolar components. It does not changed when total dose increases.

The other, SiC, is an emerging technology. Today, the components come from laboratories, not enough debugged to be commercial. One of its main characteristic is the ability to support very high temperature. So, components could be use for ITER inspection missions.

A transistor (biased at -12V during irradiation) has badly recovered (an other sample has been destroyed during this period) to reach 10MGy.

The second campaign, using SCK/CEN facilities to be neared ITER goals, could not be a remake of the previous one. Even if for few components, data could be taken through previous results, too much parameters are uncertain.

Firstly, we have never met such high dose rate (up to 30kGy/h). The early hours of irradiation get sometimes information on the establishing of permanent state.

Secondly, the short period (3 weeks) and the distant area of irradiation do not simplify management of experiments. Risk is important to test components unable to give significant data.

Thirdly, no such level of temperature has been requested in our background. If for an electronic component, thermal annealing is well known to recover characteristics off line, the combined effect of dose and temperature is an open subject.

Due to these reasons, we have been opting for in-line measurements with a specific measuring method.

To make it into action, we chose MOS transistors. We justify this choice because these components are useful for low and high power applications and already used on real conditions under irradiation. We have many results on previous irradiation tests and good feedback about applications using it.

We have been designing a new testbed based on existing one to take into account ITER constraints et developping specific test cards and wires to connect them to BRIGITTE plugs.

Figure 3 shows one of the MOS testbeds use in our lab. ITER testbed is similar to it.

Figure 3 : Instruments used to evaluate components after steps of irradiation (see an other card used for 10MGy campaign)

During irradiation, component is biased. Many types are used (+/-10V, 0V, +5V, alternate +/-10V and unsupply).

Parameter Vgs is followed by on-line tests every defined period (one hour). Bias Vgs voltage is switched to test Vgs voltage. The measure of Vgs give significant data on the ability for the component to be able to change state, from blocking to passing (in that case, Ids must be 50mA or 100mA, mean value for a power transistor, and Vds = 2,5V).

Components (12) to be evaluated for ITER constraints is an IGBT power transistor (MOS technology mixed with bipolar). It is a recent component more and more often used now in power applications (motor driving, supplies) to replace MOS transistors. Some papers spoke about it at Garching June meeting.

The manufacturer identifier is IRGCP50U from International Rectifier.

Figure 4 show results of total dose acceptance obtains after 10MGy and a week of annealing state at 65°C the same temperature than during irradiation.

No components shown failures during that time.

Permanent state is obtained early (less than 100kGy). A drift with a little evolution under radiation could be seen for bias conditions of -10V, alternative, 0V and unsupplied. During tests, we very quickly lost the working state and never retrieve it along the irradiation period ; this is due to the limits of testbed. Annealing time of a week at the same temperature shows that an immediate recovery raises of few volts the level of permanent state. Data from bias 5V and 10V are obtained. It should be possible to say that permanent level of such biases is not so far from -20V.

SINGLE OPTICAL COMPONENTS

The irradiation has been made in the SCK\RITA facilities. This equipment is composed by several cobalt 60 radiation sources. The dose rate is rounding 3 kGy/hour.

An existing testbed and the equipment of RITA had been modified to be able to manage the experiment.

The following figure shows the experimental setup.

Photodiode photocurrent is measured by a resistance connected in series with the component. Hence the photocurrent is converted in a voltage easily measured by digital converter. The resistance value connected in serie are :

- 0.5 MΩ-0.8 MΩ HFD3013
- 4 kΩ-30 kΩ FD80FC

The experiment has been done to compensate rising and downward fibre influence by a measure of a reference fibre (canal 2 of the multimode et singlemode optical switch).

After the 36th day of irradiation we have go out the experiment of RITA facilities to observe the recovery of the different fibres and components. This irradiation stopping lasted 2 days, next the initial irradiation condition resumed.

Some results (Figure 5) are given about optical fibers during irradiation and during recuperation time. These tests on four different fibres show that we can choose a multimode fibre (SPECTRAN) or a singlemode fibre at 1310 nm (OXFORD) to perform a hardness optical link.

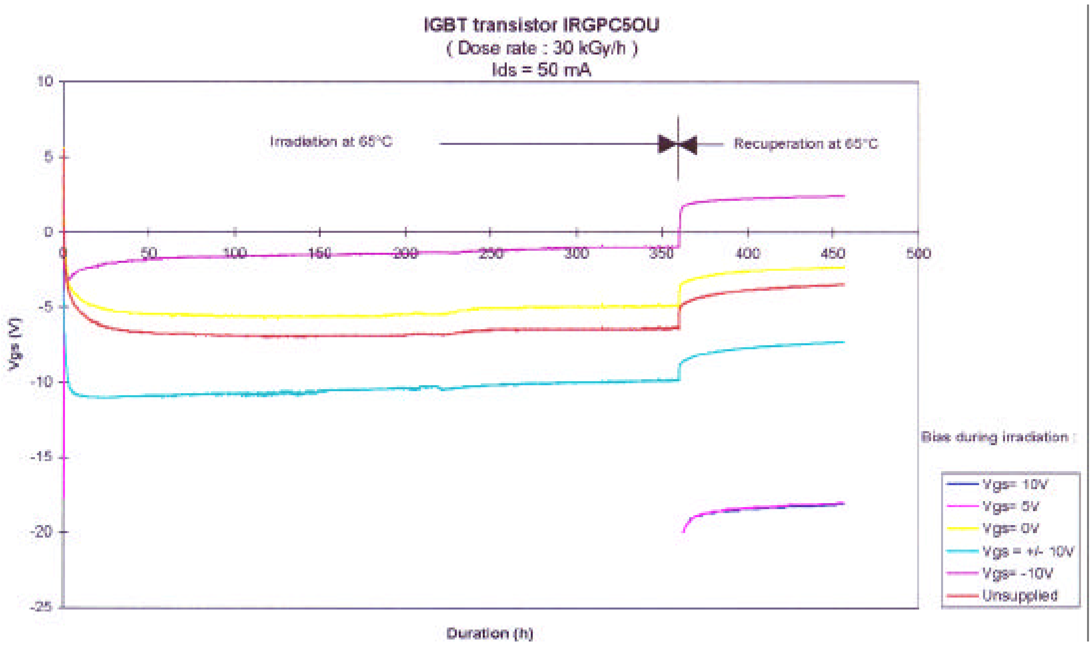


Figure 4 : Experimental data for IGBT IRGPC50U under ITER conditions

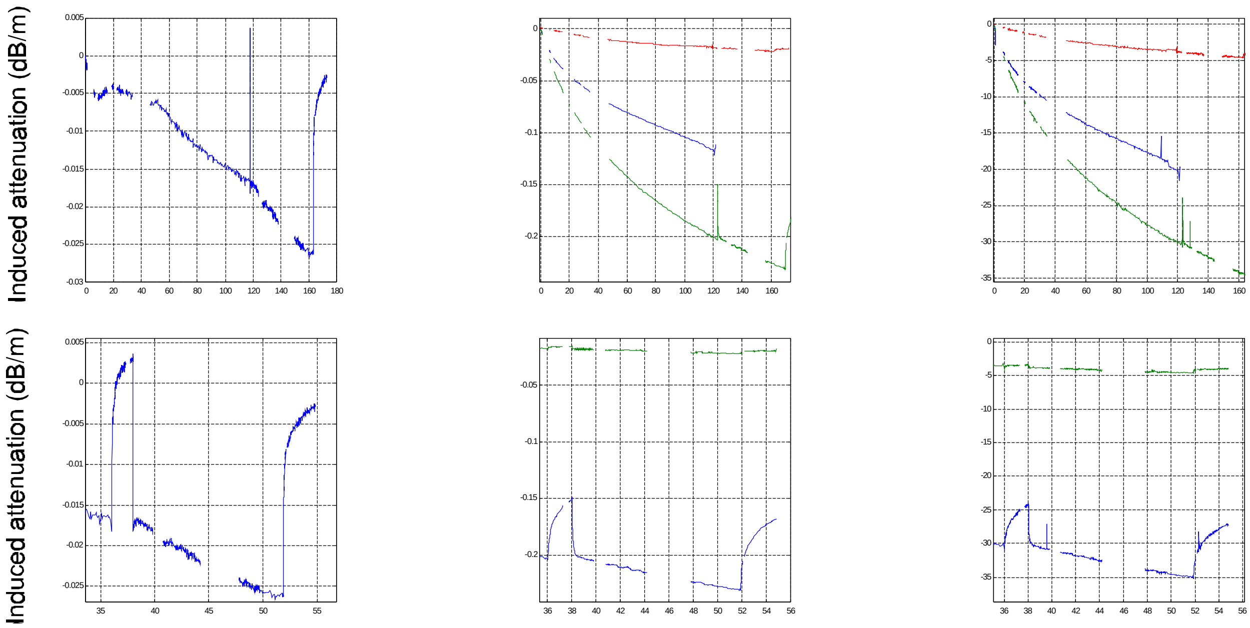


Figure 5 : Evaluation of attenuation for single and multimode fibres during irradiation and recuperation

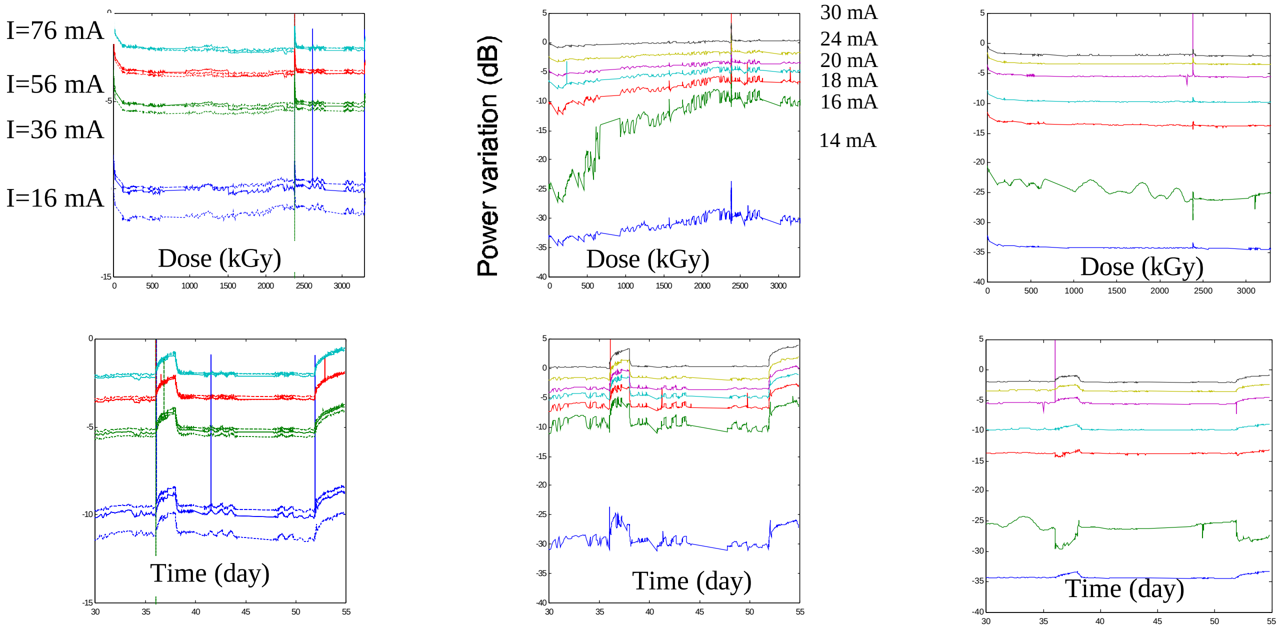


Figure 6 : Evaluation of power variation of DEL, laserdiodes and VCSELs during irradiation and recuperation

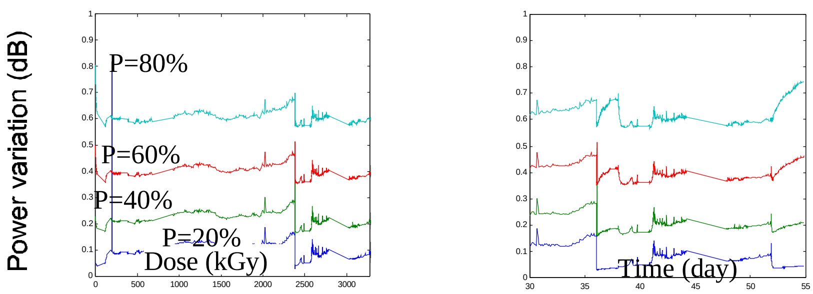


Figure 7 : Evaluation of power variation of photodiodes during irradiation and recuperation

The recovery on the CORNING fibre haven't been studied because of rupture in link between instrumentation and irradiation container.

These tests show that the fibre tend to get back to normal attenuation after a irradiation stop. But when irradiation resumed, attenuation evolution continue like before irradiation stop.

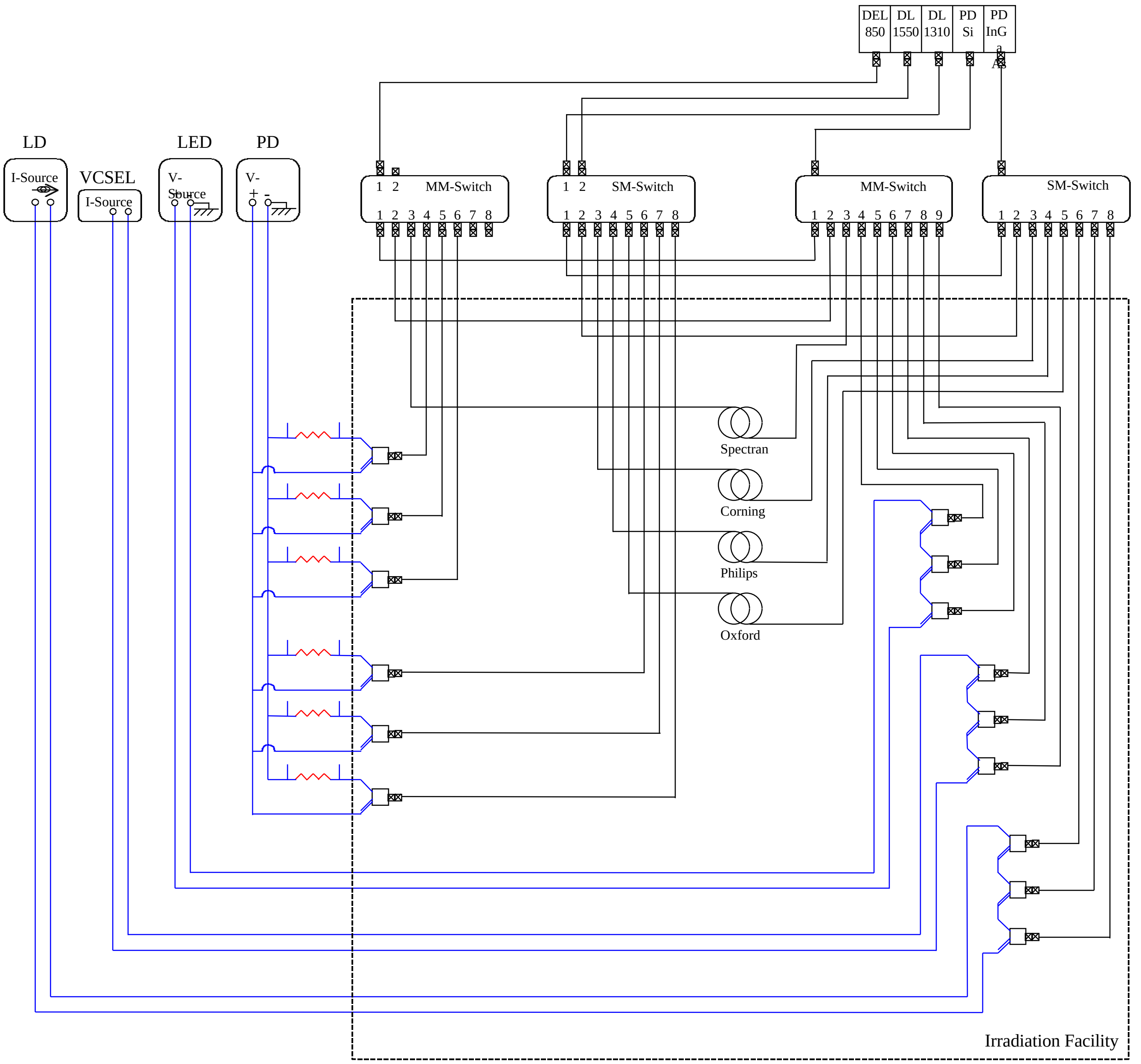
The next tests are about single optical components used to transmit and receive light. DEL, laser diodes, photodiodes and VCSEL (emerging technology for optical components) had been evaluated during irradiation and recuperation.

These test (Figure 6 and Figure 7) show that DEL have a very stable comportment under irradiation. The efficiency is rapidly decreased of 2dB, and after the comportment is very stable. The component find is initial efficiency after irradiation stop.

Like DEL, efficiency of laser diode loss 2 dB, and this modification can be recovery by a irradiation stop. Irradiation tend to change threshold current and electro-luminescent effect before laser effect, but most of time this part of characteristic is unused.

The VCSEL irradiation show a good comportment of this component. The only influence is a small fall of the ficiency (rounding 1 dB) and for one component an instability power at 4 mA (an unused current).

On this experiment, it seems that the optical link between instrumentation and component has been damage. So the optical power on this photodiode wasn't enough to make an good measure. Nevertheless we can remark a modification of the comportment for a dose rounding 2 MGy.



CONCLUSION

Due to the very short time from the end of first campaign irradiation under ITER constraints, we have not had enough time to analyse all the measured data. But the preliminary results on some important electronic components (if we included results of previous campaign) are cheerful. They tend to show that designing specific modules using these components and taking into account the shown degradation (permanent state) of main parameters could be reach for ITER maintenance missions and could contribute to reduce number of wires on the umbilical.

Emerging technology have shown mainly good response to 10MGy. It should be important for task T252 to follow these technologies which could be an answer at the design time of ITER future machine.

This preliminary results tend to demonstrated that the weakest element for an fibre link is the photodiode. Multimode and monomode fibre can be used without a great variation of their attenuation, as well as emitter element like DEL, VCSEL, and DL.

An efficient optical link for remotely controlled handling unit will require to test more photodiode type.

The necessary work to perform during beginning of 1999 will take into account the influence of temperature and irradiation on the behaviour of same components than in 1998. The results of theses experiments could give an answer to the use of electronic for short time inspection missions. Temperature levels expected are 140°C and 200°C. Nothing is really known about the ability of each element to support such environment. We must be careful and increase the control of testing supports (cards, wires, connections, weldings, ..).

In the same time, testing supports will be made for logical components in order to test them during second or third trimester.

For optical components, irradiations will be scheduled to continue the evaluation of total dose acceptance on laser diodes, VCSEL and optic fibers (single mode and multiple mode) in order to reach ITER level constraints (in 1998, steps were around 3MGy) .

With SCK-CEN teams, a large number of photodiodes will be irradiated in order to be able to select the hardest ones.
The evaluation of temperature in the behaviour of optic components will be engaged.

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Task Title : BORE TOOLING FOR DIVERTOR COOLING PIPE

INTRODUCTION

The present concept of ITER includes hundred of pipes, most of them are associated with the divertor cassettes. These pipes must be severed, when these cassettes are removed during the reactor maintenance shutdowns. The objective of the task is to design, to procure and to qualify three operated tools :

- Cutting Tool Head
- Welding Tool Head
- Inspection Tool Head

So that to cut ,to weld then to inspect the pipes.

In this frame work the Ultrasonic Testing Method Laboratory part of CEA/DPSA/STA is :

- In charge of the working out of an ultrasonic method devoted to the weld of 160 mm diameter tube. This method is to be applied from its inner side.
- Involved in the method implementation through the Inspection Tool Head which is developed by COMEX TECHNOLOGIES.

1998 ACTIVITIES

The last step of the study achieved this year, was to finish the integration and to qualify the ultrasonic method, validated in the first step in 1997, in the Inspection Tool Head developed by COMEX TECHNOLOGIES.

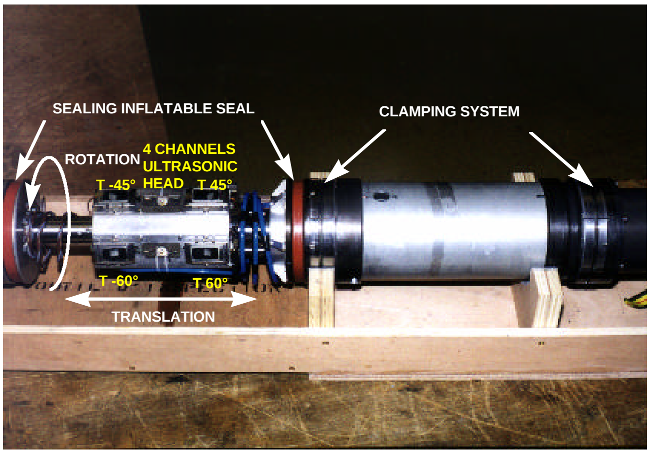

Figure 1 : Inspection Tool Head

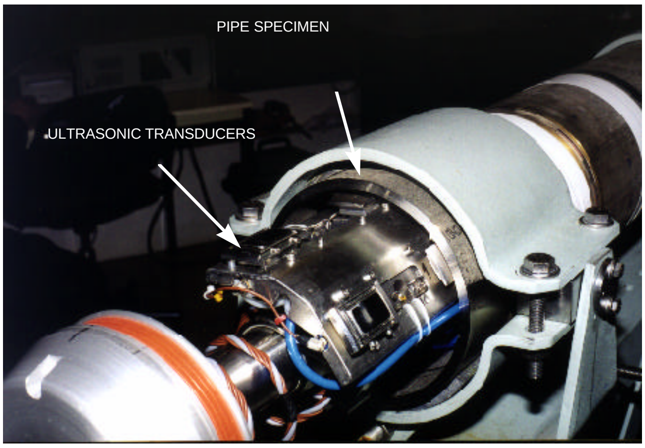

Figure 2 : ITH in the calibration mock-up

The qualification of the tool have need some adjustments and improvements before operating tests. The qualification has been performed successfully on three welds.

The first qualification acquisition was made on the calibration mock-up with artificial defects machined in during study in laboratory. The results of this ultrasonic data acquisition was compared with good accordance with the results obtained in laboratory during the first step of the study.

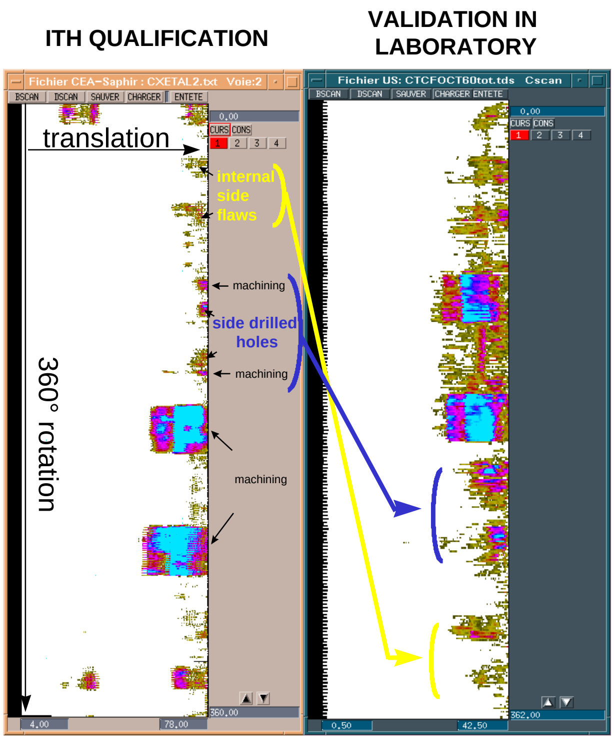

Figure 3 : Calibration mock-up, detection results on the T 60° way

The following acquisitions were made on two welds realized in operational conditions by the Welding Tool Head. We obtained in both cases some complete inspection results. One of the specimen have a lowest thickness. In this case the acquisition parameters must be adapted.

The qualification have been realized with a laboratory acquisition software specifically modified for that purpose. This software is running on a personal computer dedicated to the ultrasonic data acquisition. The ultrasonic data can be controlled by an imaging software just after the inspection with the same computer. The expert software CIVA was used to produce the detection results.

CONCLUSIONS

The ITH associated to an ultrasonic data acquisition system is able to inspect the whole cooling pipe weld.

All parameters described in the operating instructions are validate by the qualification.

In specific conditions, the method can be applied to a different pipe thickness but with other acquisition parameters.

The ITH qualification confirms the system's capability to obtain complete exploitable data file during a cooling pipe weld inspection. The system uses 4 ultrasonic channels with 45° and 60° shear waves contact focalized transducers.

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T329-2

Task Title : MAGNET FEEDER LINES AND CRYOGENIC CONNECTORS MAINTENANCE

INTRODUCTION

The R&D program carried out by the teleoperation and robotic section of CEA/STR was to demonstrate the feasibility of a representative in-cryostat remote repair operation on ITER magnet system components. While all the components inside the ITER cryostat are designed to last the lifetime of ITER without requiring inspection or maintenance, provisions are made for unscheduled inspection and/or repair interventions. Although hands-on emergency repair operations are intended to be the reference scenario, in-cryostat remote handling access and operation will be required when the environment inside the cryostat will exceed the radiation level which prevents human intervention. A typical repair operation on ITER super conducting magnet system component has been selected as a reference.

1998 ACTIVITIES

The R&D programme was set up to demonstrate that :
a) the electrical insulator of one magnet cryogenic cooling system line can be replaced remotely,
and
b) a magnet current feeder connector can be disconnected and re-connected remotely.

A full model of ITER machine, set up on a CAD system. The system is equipped with a robotics package which is used to determine the manipulator/transporter system to be used for the reference repair operation (Fig. 1).

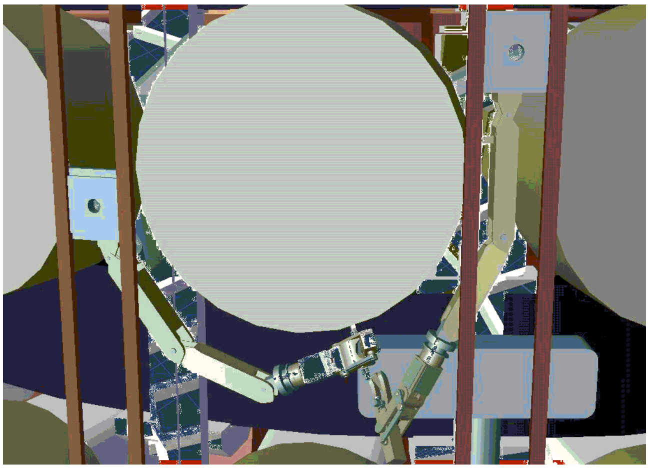

Figure 1 : Remote repair, CAD analysis

Following the above computer analysis, a more specific assessment of the RH equipment requirements (hardware and control system) for the repair, with two manipulators, of a cryogenic line electrical insulator and the connection and disconnection of a current feeder of ITER magnet system was carried out. This basis was used to set up the 1:1 scale mock up tests described below (Fig. 2).

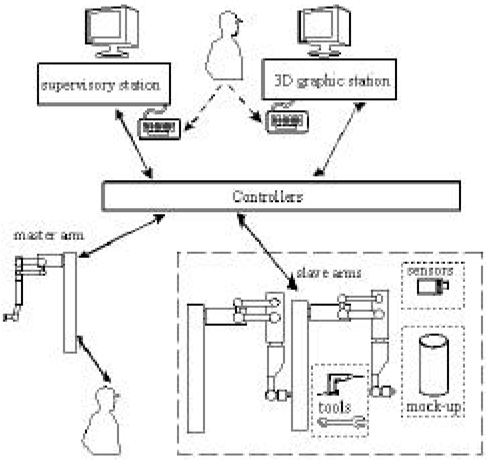

Figure 2 : Test campaign equipment description

The programme was carried out using a mock-up facility which included a fully remotely controlled robotics system with two master-slave servo-manipulators and a dedicated set of remote handling tools and jigs. The remote control station included remote cameras and was fitted with a force feed-back control system to ease the operator task.

A CAT (Computer Assisted Teleoperation) system (TAO2000) was also used to assist the operator, to increase the remote operation efficiency and to prevent collision by means of virtual boundaries.
The tests campaign addressed the following issues:

a - performance of all the elementary process tasks (cutting, alignment, welding, inspection, …) in a remote assisted mode;
b - pre-programming of the remote operation sequence and execution with a “man in the loop” mode;
c - ability to cope with unexpected situation (design of the CAT should also fit this requirement);
d - effectiveness of the graphical assistance to improve the operation speed and quality.

The above master-slave force reflecting manipulators (50 kg load capacity each) were used in conjunction with remote controlled tools based on modified hands-on welding, cutting and bolting/unbolting tools.

The mock-up included a model of a typical ITER break box, reflecting all the spatial constraints (walls, adjacent pipes, etc.). The break box mock-up was mounted such that its position relative to the servo-manipulators could be changed to reflect different positions as it would be the case on ITER. Remote cutting of a section of a cryogenic pipe, positioning of a new pipe and re-welding it was successfully tested (Fig 3.).

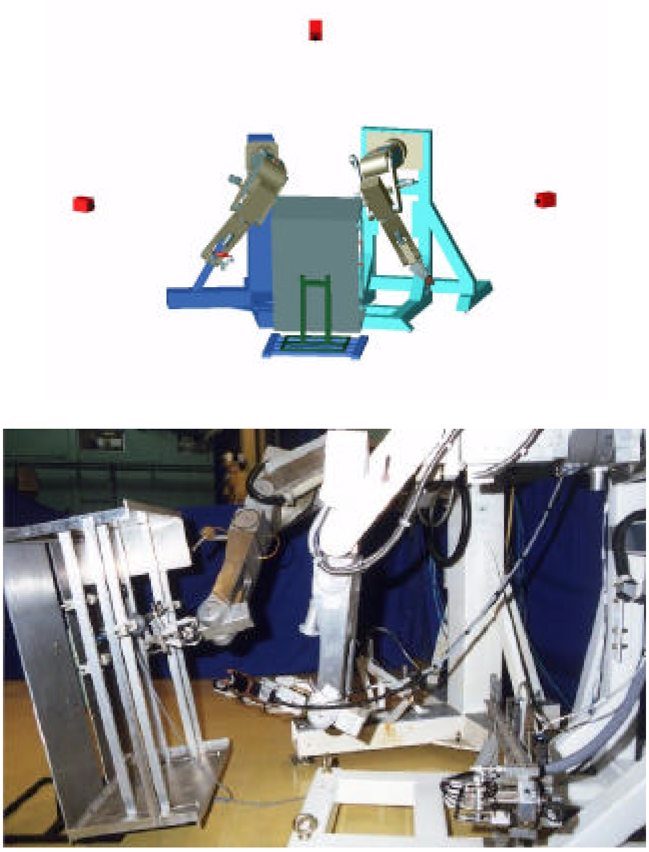

Figure 3 : Remote repair of cryoline

A further mock-up was built to simulate a current feeder disconnection/re-reconnection. The test did not address the issue of cable and feeder terminals alignment, focusing only on bolting/unbolting of the feeder clamps and on the handling/positioning of the feeder cover required for helium cooling containment. Further tests were successfully conducted to demonstrate the possibility of ground electrical insulation application to the feeder cover.

CONCLUSIONS

A test campaign on key components of the ITER magnet system indicated that basic repair operations can be successfully performed remotely with the aid of suitably designed CAT system to drive two manipulators. The tests provided useful indications for improving the design of the above components. Recommendations for ITER design have been produced therefore.

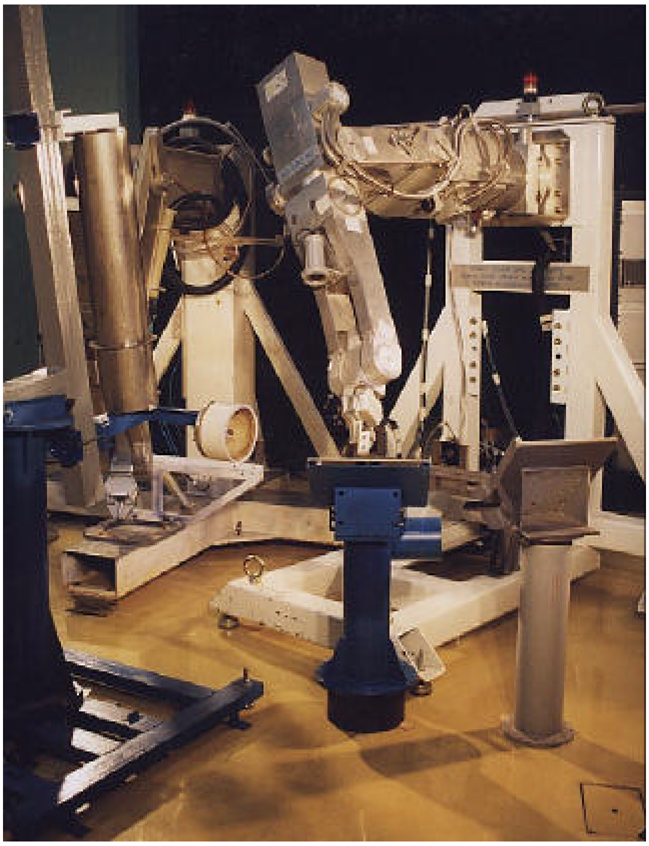

Figure 4 : Remote repair of current feeder line

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T329-4

Task Title : CARRIER AND BORE TOOLS FOR 4" BEND PIPES

INTRODUCTION

This project is an R&D program in remote handling activities for Fusion reactor In Vessel maintenance.

The removal/installation of Vacuum Vessel components often requires cutting, welding and inspection of cooling pipes. To allow the replacement of these components while minimising the space requirements, bore tools are preferred to orbital tools for these operations.

Following the latest ITER developments, an effort to standardise the pipes inside the cryostat is underway. One of these standards could be 4" pipes (100 mm ID). These pipes will be bent with a bending radius greater than 400 mm and cutting / welding will be required up to 10 meters away from the tool insertion point.

The objective of this task is to demonstrate the feasibility to operate with bore tools in 100 mm bend pipes and to study the associated mechanism required.

This task includes design activities, manufacture and testing of a demonstrator of the basic steps of 100 mm bend pipes maintenance.

1998 ACTIVITIES

This year the study is focused on the analysis of the intervention in these pipes, the design of the carrier with associated bore tools and the manufacture and testing of a demonstrator of the carrier.

ANALYSIS

The status of piping inside Fusion reactor machine induces different isometric constrains on bore tools and carrier design.

The analysis of the intervention inside bend pipes induces the use of a modular carrier concept with 4 main functions :

- set up tools from pipe entry point to working zone,
- position tools at the correct location,
- generate stress in pipe :
  - clamping on pipe,
  - compensate internal pipe stress after cutting,
  - align two faces of pipe before welding;
- and rescue of the system.

The carrier should also onboard tools required to proceed to the maintenance operations. The required tools functions are :

- Milling, to cut 80% of the pipe
- Final cutting with a cutting disk
- Tack welding
- Butt welding with filler metal
- Non destructive testing to check the quality of the operation.

One of the major difficulties for the design of such carrier is the lack of space to onboard all the required devices, to produce enough forces, to deal with bend pipes during progression.

We therefore proposed an optimised concept that consist in a flexible modular structure, able to be rigidify, that onboard process devices in the modules.

The basic case selected to drive the design activities concerns the Divertor cooling pipe with various possible interfaces. Possible cases are semi-embedded or embedded pipe which directly influence the flexibility of the pipe that the carrier should connect/disconnect.

These cases have been analysed. It shows the need of 100 daN level of stress generated by the carrier to align the pipe before the welding operation within 20 mm maximum free space along pipe axis and 10 mm radialy.

The main issue to demonstrate the feasibility of the intervention is focused on the operations which requires the use of a process while maintaining the pipe on place (compensation of internal pipe stress) : the final cutting of the pipe requires to compensate internal pipe stress, tack welding induces alignment of the two faces of pipe. Those are the two selected operations to demonstrate.

CARRIER DESIGN

The carrier should be flexible in order to progress into bend pipe, and must rigidify along the intervention area when process requires to compensate heavy loads.

The carrier is made of cylindrical modules dedicated for various functions with flexible links to progress along bent pipes.

When in the intervention area (straight part of pipe), a cable mechanism assembles the modules. Carrier is now a rigid structure with good capability to generate stress in pipe.

Carrier modules are also equipped with clamps to lock inside the pipe.

Carrier motion is controlled from outside the pipe with a glass fibre flexible rod which could be assisted, if necessary, by a specific propulsion module when motion required forces become too high.

After end of cutting or before welding operation, the carrier should compensate the stress of the pipe in order to separate / reassemble the both side of pipe along the interface.

Therefore, a front process module is required to produce stress inside the pipe. Previously, the two faces of the pipe have been aligned by the carrier itself.

Other modules are dedicated to support and carry out process operations.

TOOLS DESIGN

The study concentrates on final cutting and tack welding because it allows to demonstrate all the major difficulties.

The final cutting tool ends the cutting of the pipe after the milling process. The milling process only produces 80% of the cut, avoiding schwarff off the pipe. When the cut is achieved, the carrier should compensate the constraints between the two parts of pipe in order to avoid jamming of the tool.

The tack welding tool is located in the Front Process Module (FPM) of the carrier and should perform 3 tack welding points at 120° in the welding groove of the pipe after the carrier had been aligned and approach the two faces of pipe.

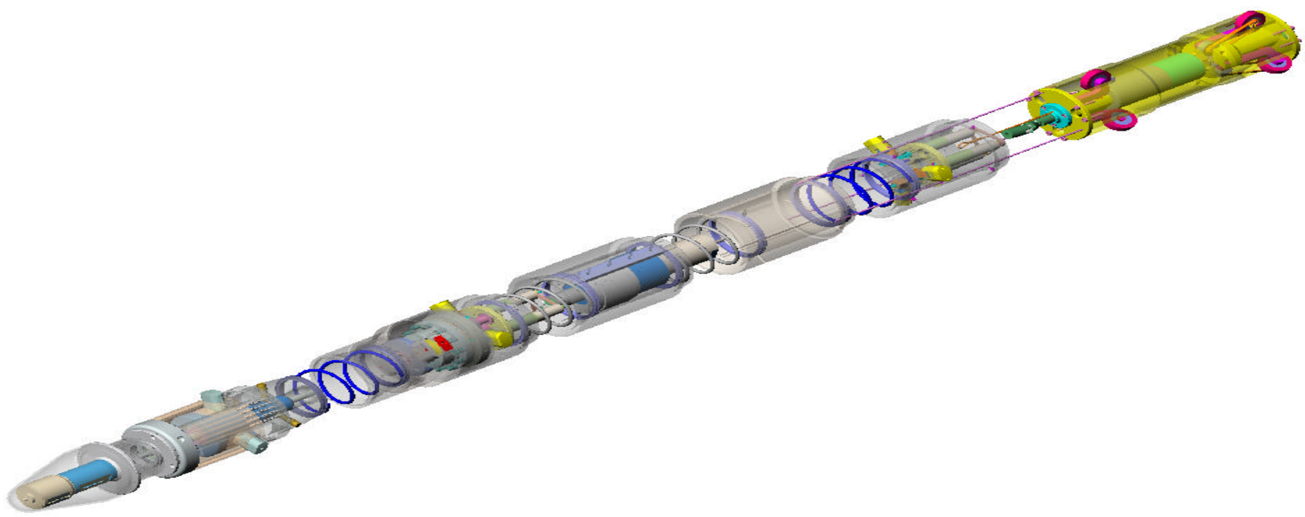
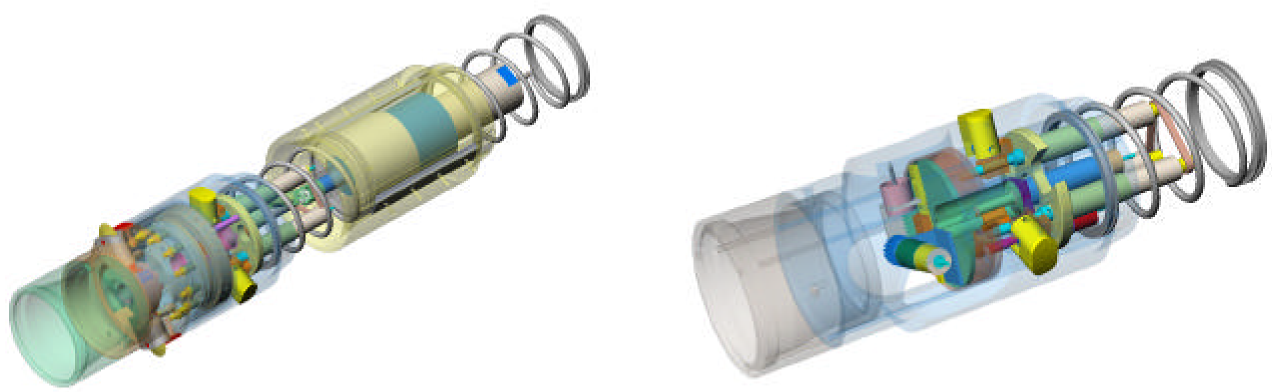


Figure 1 : 3D view of the CARRIER



Final Cutting Tool

Tack Welding Tool

Figure 2 : 3D view of the tools

DEMONSTRATOR MANUFACTURE AND TESTING

A demonstrator of the basic functions of the carrier has been manufactured and tested to qualify its principles :

- Displacement, in a bent pipe, of the carrier by means of a flexible rod,
- Assembling, along the straight part of pipe, of the carrier by means of traction on cables,
- Correct positioning,
- Clamping inside the pipe,
- Alignment of pipe prior to tack welding, axial and axial drive of the pipe with the carrier.

Figure 3 : Demonstrator of the carrier's basic functions

CONCLUSIONS

The analysis of the maintenance operation has been performed and an innovative modular system of carrier and tools has been proposed that fit all the requirements.

The carrier and the associated bore tools has been designed.

A demonstrator of the basic functions of the carrier has been manufactured and tested. The first test campaign shows that it reaches the required values of performance.

The future work program consists in the following steps :

- Manufacture and testing of a complete carrier (without process tools).
- Manufacture and testing of two tools identified as highest issue, the final cutting tool and the tack welding tool.
- Test and upgrade of the complete equipment (carrier with embedded tools).

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T329-5

Task Title : IN-VESSEL RH DEXTEROUS OPERATIONS

INTRODUCTION

Scope of this work is to carry out an R&D program to demonstrate the feasibility of an effective remote handling dexterous operation that takes place within the Divertor RH maintenance.

The maintenance operation will be performed under so called « blind » conditions (without video feedback assistance) based on 3D graphical model assistance. A Divertor Test Platform has been set-up in Italy (ENEA site) to demonstrate the feasibility of such maintenance for nominal conditions. An open issue of such operation concerns the demonstration of unexpected situation specially when rescue mode is required.

The main concern of this R&D project consist in the demonstration under real remote handling conditions such force feedback device can afford with unexpected situation in rescue mode. Therefore, a demonstration is foreseen on the Divertor Test Platform at ENEA site.

1998 ACTIVITIES

Project T329-5 started in July 1998.

Specification of the RH operation has been defined with a special issue concerning the definition of the rescue scenario to be taken into account. The situation takes place within the divertor region located in-vessel at the botomside.

The rescue scenario finally defined is the following :

1. CTM to release the cassette,
2. CTM backward by monitoring driving motor currents (few tens of cm to allow enough free space for MAM operation),
3. MAM , with tactile sensors, to position the CTM / rails, to send to the supervisor the real position of the CTM,
4. CTM toroidal re-positioning (Operator in override mode),
5. CTM backward to RCC (for example) for position sensors re initialisation,
6. CTM forward the cassette at low speed (5 mm/s) up to the detection of the cassette by means of one CTM US sensors,
7. CTM backward a few cm to provide enough space to the MAM operation,
8. MAM with tactile sensors, to send to the supervisor the real position of the cassette,
9. MAM to check and totally unlock if needed both CLS,
10. Use of the real cassette position at the supervisor level to prepare the cassette mission rescue :
    - correct toroidal alignment of the cassette (over-ride mode)
    - removal of the cassette (nominal mode)

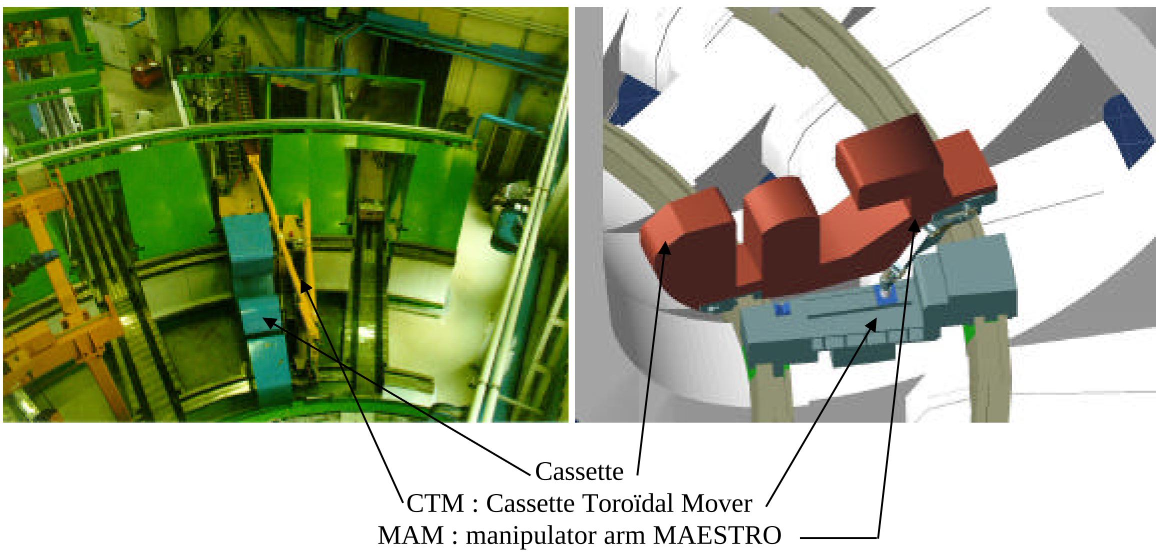


Figure 1 : RH operation

Once the mission defined and specification completed, the work has been focused on the graphical model to be used for RH assistance. The mission can be prepared off line using a geometric model of the DTP. Since, the system used at BRASIMONE for DTP modeling by ENEA is DENEB 's CAD system TELEGRIP, and system used at C.E.A / STR is derived from ALEPH 's ACT CAD system, a graphical model adaptation is required. Both these systems are CAD robotics systems. They provide different kind of functionality but are completely disconnected : one can't be included into the other one.

The work has then consisted on adaptation of the graphical model of the mission environment based on IGRIP software to have a graphical model compatible with TA2000 Teleoperation system developed by CEA. To respect the performances, it must be considered the obstacle avoidance and visualisation of 3D models. We have demonstrate the possibilities to work with a model comming from ENEA site.

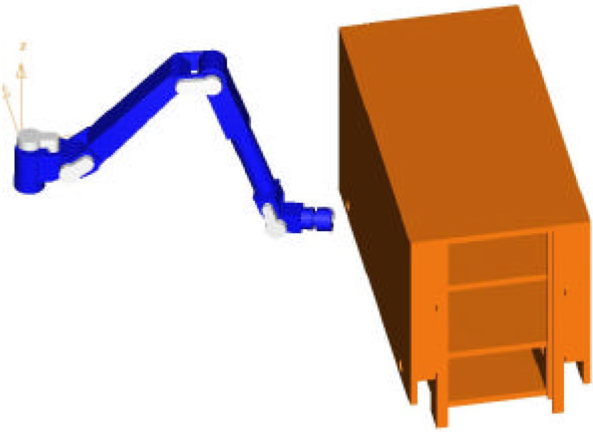


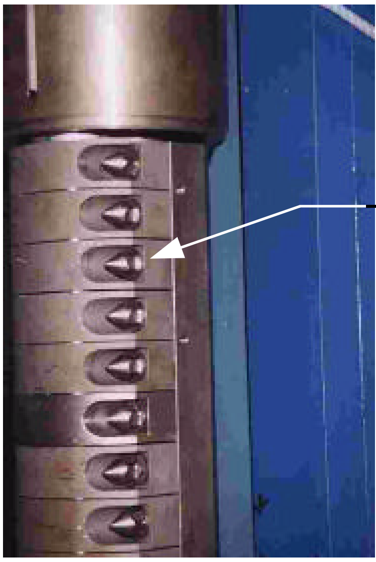
Figure 2 : MAESTRO and DTP tractor

We then experiment some of our obstacle avoidance and trajectory generation algorithm successfully with this model. We, finaly, procured a specification document to focus ENEA work to built the 3D environment of the DTP.

After graphical model adaptation task, we analysed and validated the feasibility of remote manipulation in blind conditions based on graphical model assistance.

Trials and evaluation of remote manipulation and bolting operations in blind conditions have been performed using the experimental site set up for the Fusion project, « Magnets feeder lines and cryogenic connectors Maintenance », which is composed of RD500 slave manipulators controlled with TAO2000 remote control system and the mock up of magnet system electric feeder line connectors. This experimental site represents realistic conditions to carry out such analysis and validation with time and resources saving since it is already set up.

Selected operation for this demonstration is the bolting operation of the two clamps on the connector core. The mock up features are illustrated below.



Clamps to bolt

← Electric connector

Figure 3 : Electric connector

Three steps have been executed to validate the feasibility of remote manipulation in blind condition :

REMOTE MANIPULATION BASED ON GRAPHICAL ASSISTANCE WITHOUT POSITIONING ERRORS

In that case, remote operation is done with only graphical assistance, video camera feedback is switched off.

The graphical model fits « perfectly » the real mock up environment so the operator has not to overcome positioning error. In this ideal case (positioning errors less than 5 mm), we have analysed the effect of the graphical based remote operation.

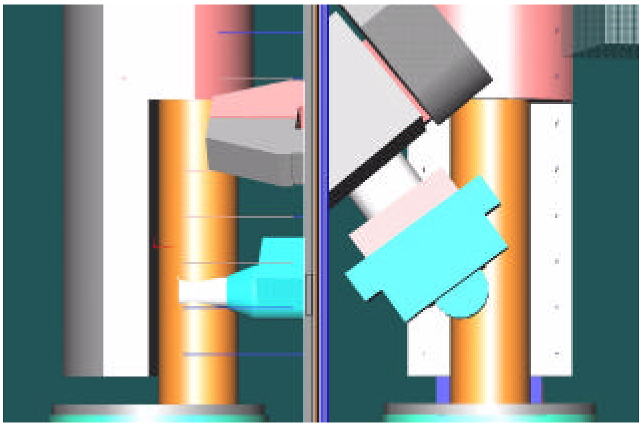


Figure 4 : Right and front view of the graphical model of the connector

The same view in line graphical configuration :

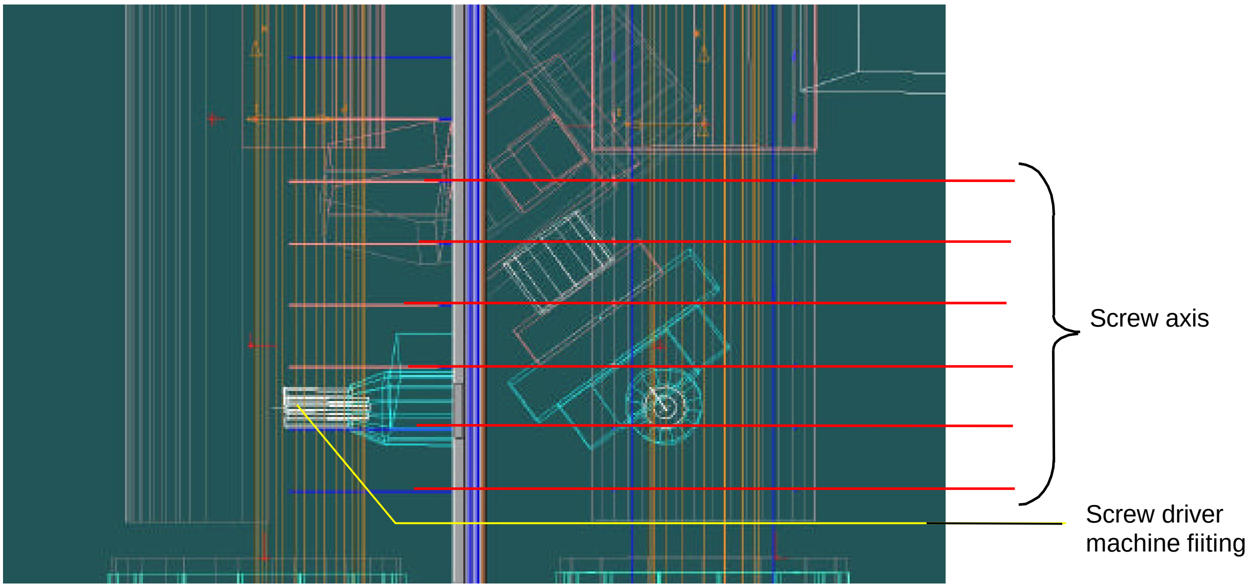


Figure 5 : Right and front view « in line » of the graphical model of the connector

In these conditions, we have demonstrated that RH operation could be done in safe and efficient way.

REMOTE MANIPULATION BASED ON GRAPHICAL ASSISTANCE WITH POSITIONING ERRORS

Connector mock up is shifted by +/- 25 mm from original position used for graphical modelling. Trials in that condition have shown that RH operations are difficult and not reliable.

CALIBRATION OF GRAPHICAL MODEL

To be able to work in conditions close to case 1, calibration of the graphical model is required. This operation is essential since RH operation based on graphical assistance is achievable only if positioning errors are limited. Calibration is performed by the manipulator equipped with range finder sensor and remote controlled in Master/Slave mode by the operator. This calibration procedure done in « blind » condition requires the operator to sense characteristics features of the environment to calibrate (as plane surfaces) thanks to force feedback capabilities of the system. Results of these experiments have demonstrated that the size of surfaces to measure for calibration is critical and that a minimum size seems to be close to 100 mm x 100 mm.

CONCLUSIONS

The work carried during this first phase of the project pointed out the feasibility of two critical point :

Adaptation of the graphical model to get IGRIP models from ENEA into TAO2000 system is possible through DXF format exchange. RH operation in « blind » condition is achievable with some constraints : calibration is a critical step to overcome, to get the graphical model to fit the real environment, thus measurement features like surfaces with minimum size of about 100 mm x 100 mm are required.

The project is now running the following steps :

- mission analysis
- RH tool and light mock up design and manufactory,
- preparation of mission at Brasimone,
- mission final demonstration.

In addition, three sub-tasks have been considered in order to follow fusion requirements :

- Absolute positioning of the manipulator within its real environment, considering advanced technics to optimize use of contact sensors.
- R&D activities for the use of pure water hydraulic actuator for force feedback manipulators in order to respect environmental requirements.
- The study of a long distance remote handling intends to improve advanced maintenance for ITER : remote maintenance with support of several expert located at long distance various sites, advanced remote diagnostics .... are fields of interests for large project like ITER.

These sub-tasks will start beginning of 1999.

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UT-RH1

Task title : TECHNOLOGY AND CONTROL FOR HYDRAULIC MANIPULATOR

INTRODUCTION

To adapt and improve hydraulic technology and control for fusion remote handling hydraulic manipulators :

- development of force and hybrid control,
- integration of specific hardware to simplify electronics and wiring for nuclear hardening, and to improve performances.

To integrate and demonstrate these improvement on an operational manipulator.

1998 ACTIVITIES

Hydraulic manipulators are candidate for fusion reactor maintenance. Their main advantages are their large payload with respect to volume and mass, their reliability and their robustness. However due to their force control limitations, they are not relevant for precise manipulation. For safety reasons, it is required to improve force control efficiency, specially when contact appears between the manipulator and its environment for both expected and unexpected situation.

The aim of the action « Remote handling technique - Technology and control for hydraulic manipulator » during the first year was to develop force and hybrid control in order to avoid these problems. The control scheme had been developed and tested on a one axis mock-up.

In 1998, this scheme has been implemented in TAO2000, the robotic controller of CEA/STR. The MAESTRO hydraulic manipulator was coupled with a master system. The Man Machine Interface between TAO2000 and the operator is the software OTARIE. In the same time, hydraulic technology improvements have been tested. The feasibility to manufacture pressure sensor working under fusion requirements has been studied. Pressure servovalves are tested in order to control the joint without any pressure sensors.

A master / slave system MA23 / MAESTRO has been installed and tested during tasks which was performed using manual mode and automatic mode.

CONTROL SOFTWARE

TAO-2000 is a control hardware and software dedicated to Computer Aided Teleoperation (CAT). A CAT system provides the human operator with manual, automatic and mixed control modes. With such a system, the human intervenes at an execution level (in manual and mixed modes) and at a supervisory level in order to select, monitor and sequence the implemented control modes. In this supervision activity, two problems are generally encountered : (i) the operation of a basic CAT system implies specialised robotics knowledge which cannot be mastered on-line by an operator whose training is often a matter of the application domain rather than robotics and (ii) it heavily relies on geometrical data which are considered differently by the human and by the computer.

The latter difficulty may be avoided by providing the control system with a 3D model of the workspace that allows the operator to visualise and designate geometrical objects on the screen of a graphic workstation. A solution to the former problem is to assist the human with a computer possessing some description of the task : this supervisory computer is thus able to support a high-level man-machine dialogue hiding the execution details. However, a tedious and rigid "programming" phase is inappropriate as it would jeopardise the flexibility of the teleoperation system.

1. Control modes

Hybrid force-position control modes are particularly useful to perform telerobotic tasks. They aim to control position and force in separate directions and rely upon the virtual mechanism concept (figure 1). Its principle consists in simulating with the computer a mechanical linkage between the arm end-effector (actually the center of the tool frame) and the environment. The manipulator mobility is thus restricted to the motions (manually or force-controlled) which verify the kinematics of the chosen "virtual" mechanism. In this way, a wrench may be easily guided perpendicular to a surface or moved along its axis.

The system also provides full manual master-slave modes (with force feedback), in Cartesian and joint spaces. All these modes are generally combined with several other functions : master arm indexing, adjustment of master-slave ratios, dynamic balancing of a carried load and position learning.

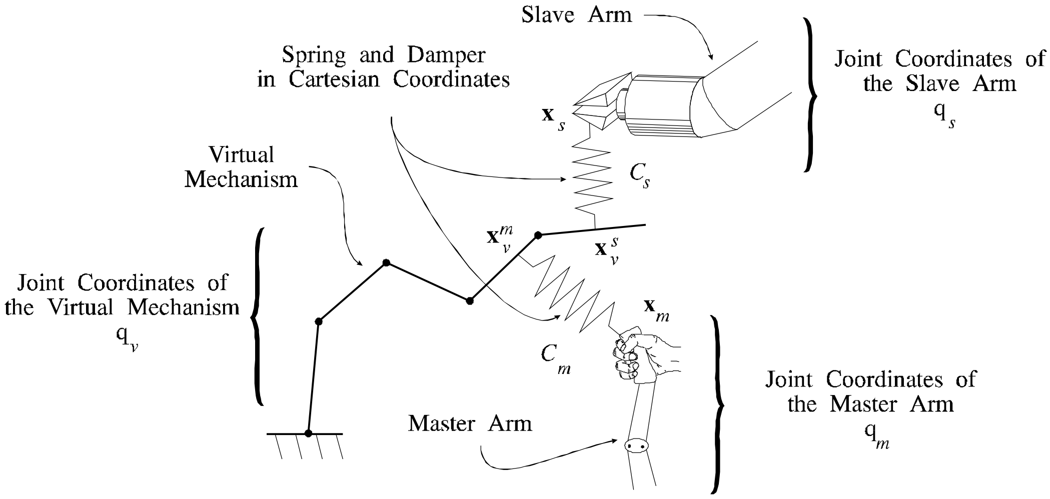

Figure 1 : The virtual mechanism concept :

2. Graphic and supervision functions

Based on a 3D model of the remote environment, the implemented 3D graphic functions provide computer-generated visual feedback, they detect and signal collision threats, they calculate geometrical parameters and compute collision-free trajectories to reach specified positions. They also permit the human operator to designate and select environment objects (like a tool or a screw). The system man-machine interface is then enhanced with a graphic workstation that displays an animated synthetic view of the workspace used as a support for the other 3D graphic functions. At the higher level, the remote work is either supervised by a program or interactively controlled through the dedicated human-computer supervisory interface.

Since telerobotic missions are generally unpredictable, the effects of a running program may be on-line adjusted, modified or countermanded using this interface. The parts played by the supervision interface are thus :

Display the system current configuration, the activated control modes and 3D graphic functions, the detected events and alarms. Provide a direct access to the system general procedures (start...), the control modes and to basic graphic functions (synthetic viewing, collision detection and trajectory generation).

The graphic functions and the supervision functions are grouped in OTARIE software. This new concept of Man / Machine Interface is represented on figure 2 :

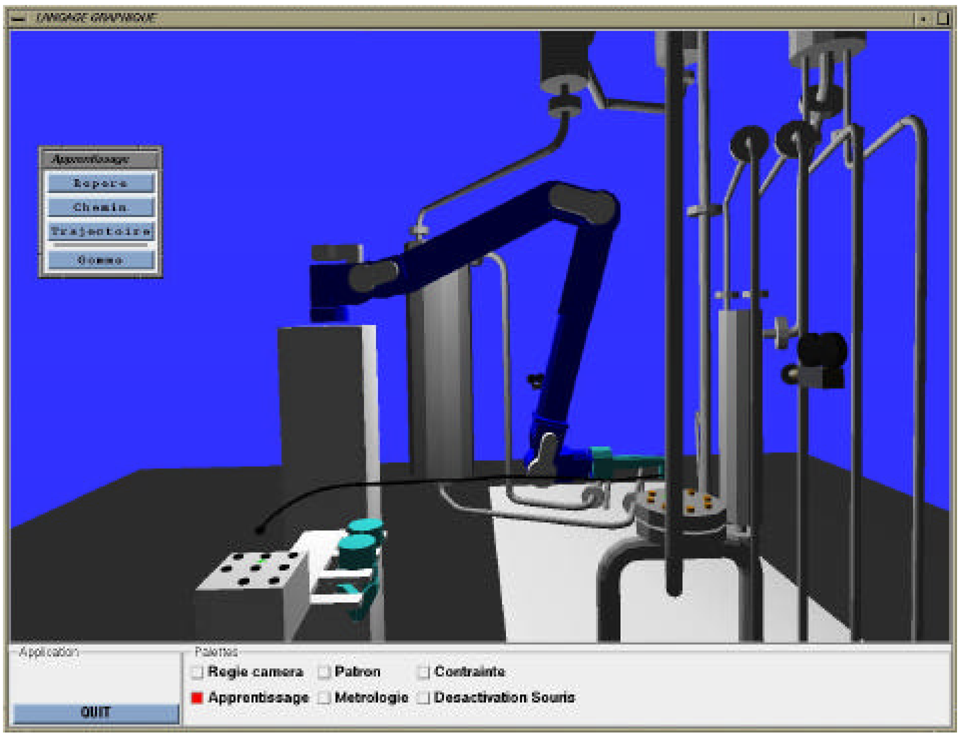

Figure 2 : Man Machine Interface OTARIE

EXPERIMENTS

The master / slave system MA23 / MAESTRO is now installed.

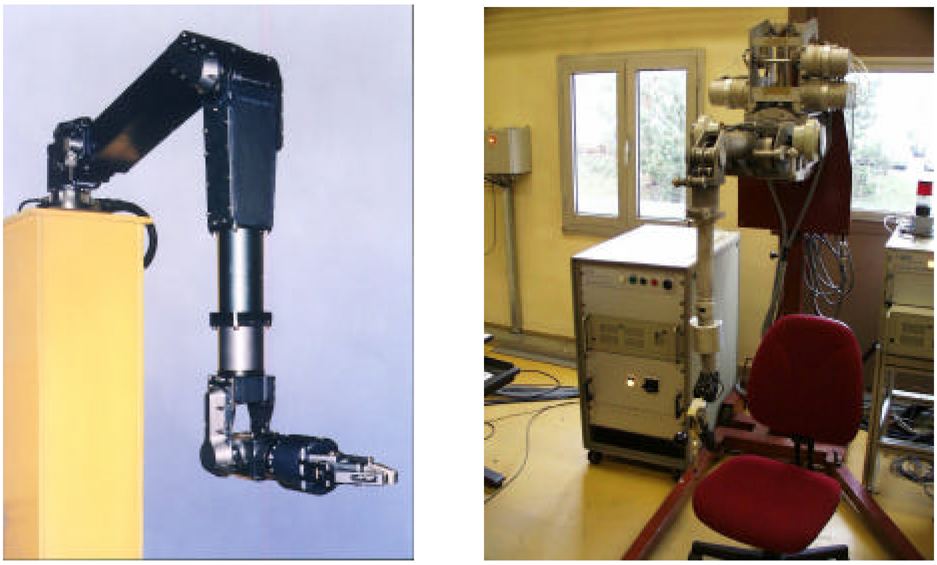

Figure 3 : MAESTRO and the ma23 master arm

This master /slave system has been tested on the following tasks :

- peg in hole (laboratory task)

Figure 4 : Peg in hole with a MAESTRO

- automatic tools exchange

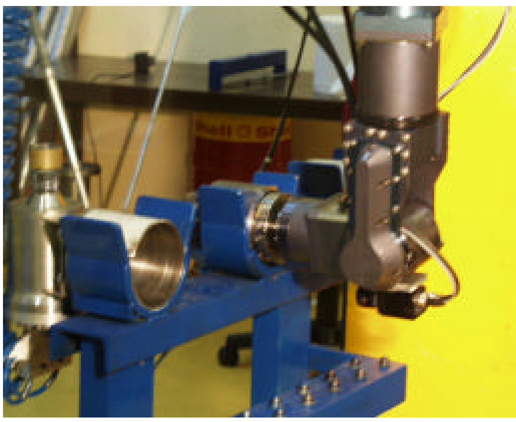

Figure 5 : Tool exchange

- screw and unscrew

Figure 6 : Unscrewing

- cutting

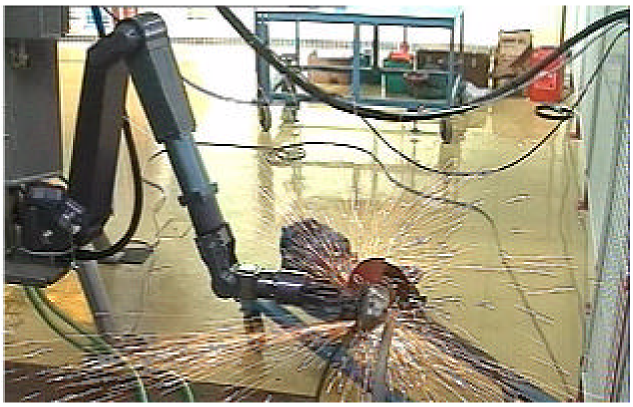

Figure 7 : Tube cutting

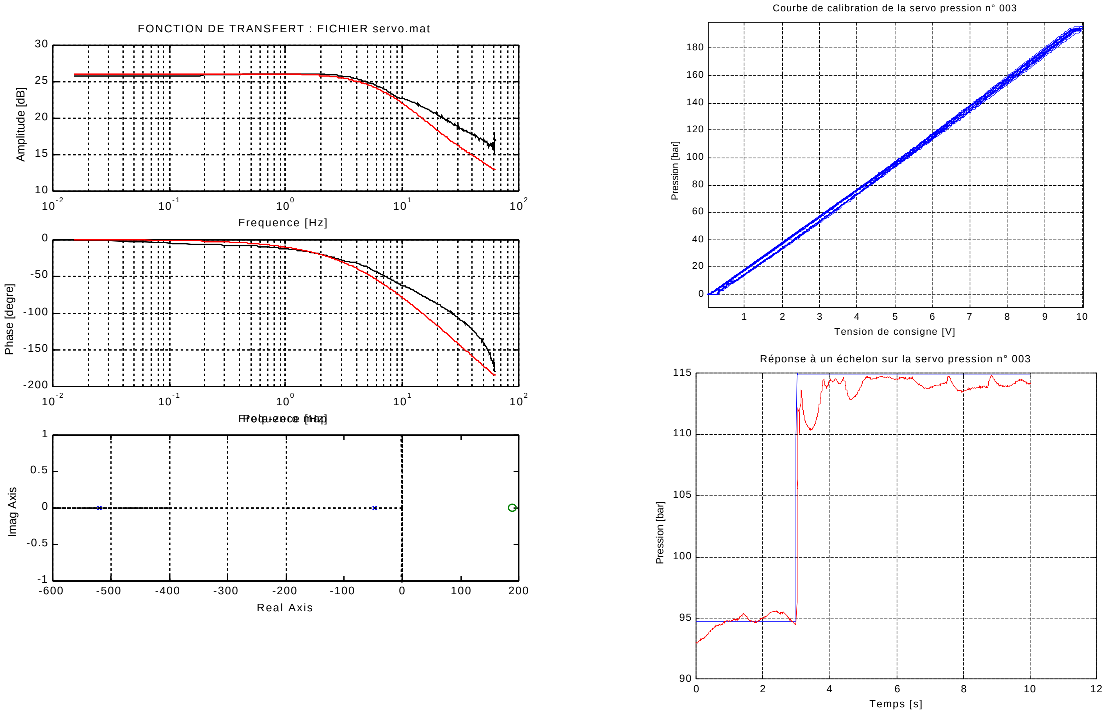

Figure 8 : Pressure servovalve characteristics

HARDWARE

On the hardware, the pressure servovalves has been tested in order to be integrated in a hybrid control scheme.

To know if the selected pressure servovalve can run in the control scheme, the performances of the servovalve has been characterized. Static and dynamic characteristic have been identified. These characteristics indicate that this servovalve allows to control the joint torque with enough precision and rapidity. So, they can be integrated in a MAESTRO.

CONCLUSIONS

At the end of this year, a master / slave system (MA23 / MAESTRO) is able to be tested on the fusion task. Development of the control software has been achieved and tested. The system is ready to be qualified under new realistic tasks.

The studies on the hardware must be forwarded. The characteristics of the pressure servovalve indicate that it could be interesting to replace the classical servovalve and the pressure sensor. This modification will simplify the hardware in terms of sensors, of wiring. The software will be also simplified without reduction of performances.

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Remote handling techniques
Technology and control for hydraulic manipulator
18 month report
F. LOUVEAU - P. GICQUEL - Ph MORGANTI

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Remote handling techniques
Technology and control for hydraulic manipulator
Final report
F. LOUVEAU

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Task Title : GRAPHICAL PROGRAMMING FOR REMOTE HANDLING

INTRODUCTION

The UT-RH2 « Graphical programming for remote handling » action deals with the programming and supervision of the remote-controlled telerobotics systems used for the maintenance of the ITER fusion reactor.

Telerobots relying upon Computer Aided Teleoperation (or CAT) techniques [1] are known to significantly enhance the performances of remote interventions. CAT allows the human operator to dynamically set the configuration of his teleoperation system in order to benefit from the most appropriate perception-action loop according to the considered sub-task. As the system generally offers different ways of achieving a remote task, the operator must select the telerobot control modes (from full manual to full automatic) in order to get the best efficiency at any moment [2].

The supervision of a CAT mission seems therefore to require a strong robotics expertise. The maintenance operators in the nuclear field are generally efficient for manually controlling telerobots, but they are not specialists in computer programming, nor in robotics. The present action addresses this problem. Its goal is the development of a man-computer supervision and programming interface relying on virtual reality techniques. Using such techniques, the supervision activities may be translated into a graphic metaphor based on a 3D realistic or symbolic representation of the work environment. This virtual universe contains a number of graphical tools that have specific behaviours and interact both with the human operator and with the modelled environment objects. Preparing and supervising a remote mission is thus expressed in terms of directly operating virtual tools like a welding device or a measuring tape without having to bother about robotics intricacies.

The UT-RH2 action has been organised into 2 steps :

- In 1997, a graphical programming mock-up implementing the virtual tools concept has been specified, developed and validated for a well known drilling task. At the same time, in the frame of action T329-2 « Magnets feeder lines and cryogenic connectors maintenance », several processes suited to the maintenance of the ITER reactor were studied and specified.

- In 1998, the previous graphical programming mock-up has been modified to deal with the programming and supervision of one of the maintenance missions analysed in action T329-2.

  This system has then been used to define a number of recommendations and guidelines for the specification of a complete man-computer interface for programming and supervising ITER remote maintenance missions.

1998 ACTIVITIES

Following its successful validation in 1997, the graphical programming concept has been developed in 1998 and applied to the supervision of a remote mission representative of ITER maintenance tasks. The 1998 demonstrator is dedicated to a pipe cutting mission performed for maintaining cryogenic connectors. It features a graphical command and programming language based on a set of virtual tools that duplicate real drawing, metrology and maintenance tools.

The demonstrator interface basically displays a computer-generated 3D representation of the workspace and the remote robotics arm called in this context the virtual arm (figure 1). The human operator may first select and adjust his visual feedback through a virtual camera module easily controlled with mouse operations. Using a 6 degrees of freedom (6 DOF) input device (either a SpaceBall or a SpaceMouse), he may then displace the virtual manipulator and simulate motions performed under manual control. Collisions with the environment are detected and signalled to the operator. The system also prevents the manipulator from « entering » inside the modelled obstacles.

The mission tested with the graphical programming demonstrator consists in replacing a part of an ITER cryogenic connector by a new pipe section. This is achieved using a special cutting device made in 2 elements that can be closed around the pipe in the area where it must be cut. The successive steps of the procedure are thus (figure 2) :

- grasp the tool,
- go to one end of the cryogenic connector and close the pipe cutter around it,
- cut,
- open the cutting tool and release the pipe,
- change the orientation of the tool,
- go to the other extremity of the connector and repeat the cutting operation,
- move the tool while it is still closed and thus holds the free part of the pipe,
- go and ungrasp the tool and the pipe.

All this mission is performed inside a tight volume with numerous potential obstacles.

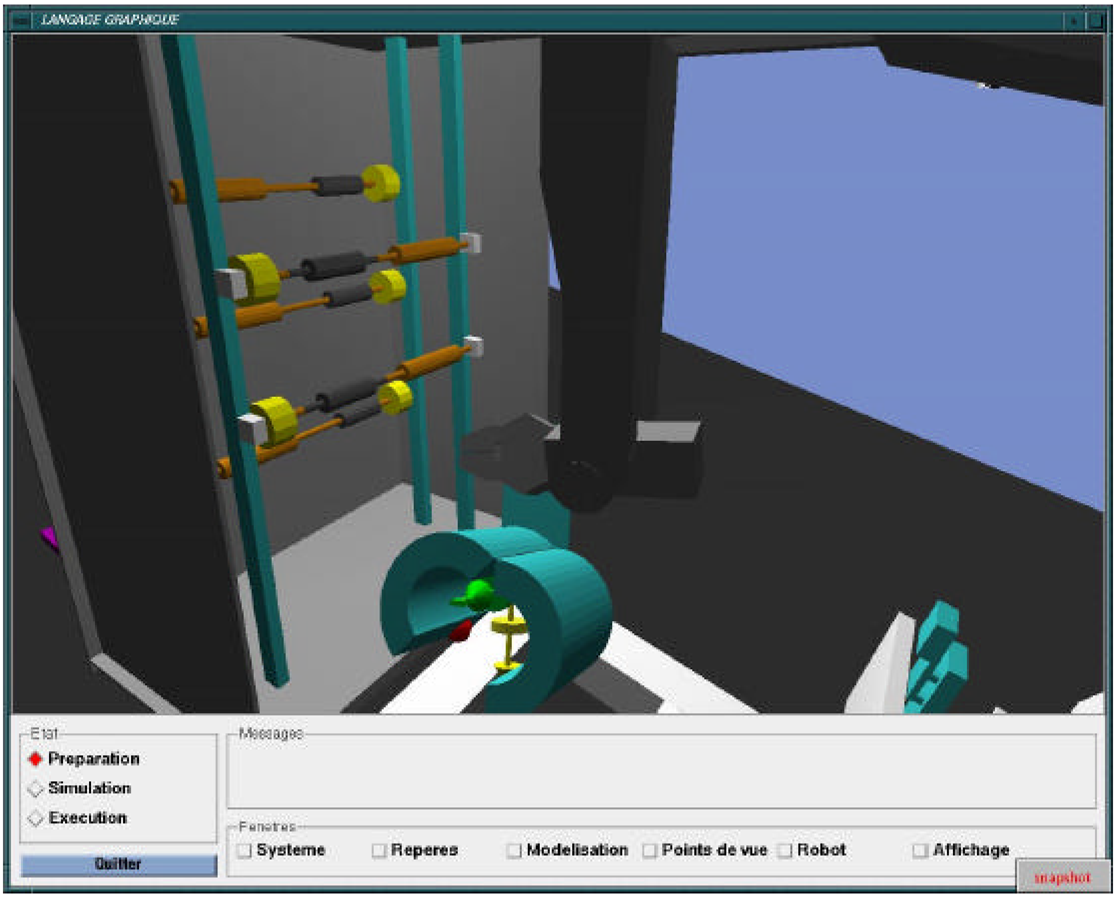

Figure 1 : General view of the ITER Graphical Programming demonstrator interface

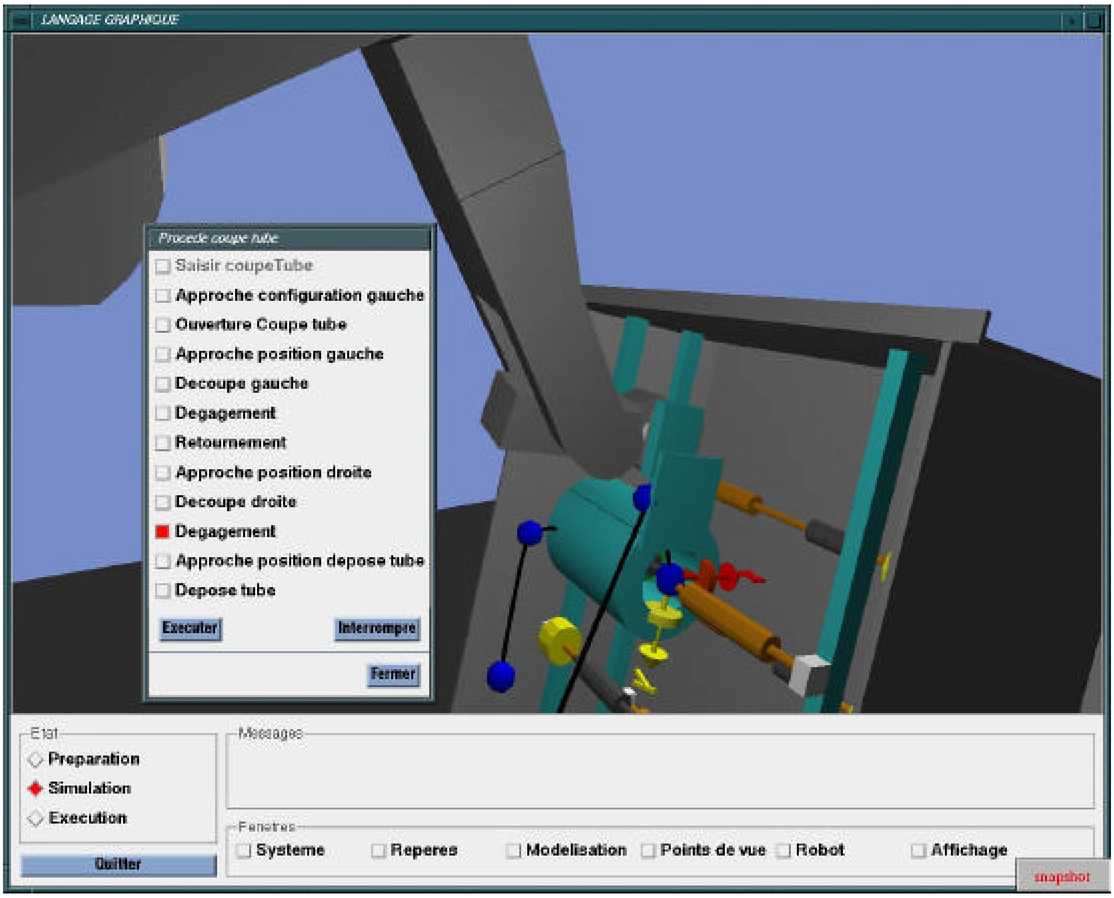

Figure 2 : Simulation of the pipe cutting process showing the operation list displayed to the operator

In this context, the main task of the operator is to specify the work that has to be remotely performed. This is achieved by interacting inside the 3D graphic environment with various virtual tools :

- some of them represent the real tools used for the maintenance operation ; a model of the pipe cutter thus materialises the main process of our mission ; its main purpose is to allow the operator to control tasks like grasping the tool or cutting a pipe ;

- some others stand for the robotics functions that are involved in the pipe cutting mission ;

- the last are used to define the geometrical parameters of the previous functions or tool operations.

All these graphical tools have their own graphical shape and behaviour that simplify their utilisation by the human operator. To start the mission, the operator designates with the mouse the cutter tool and the pipe to replace.

A window showing the various steps of the mission is displayed on the 3D virtual environment. In this case, the main difficulty is to specify the trajectories that the manipulator will follow, especially when it is carrying the tool and a part of the pipe. To do that, the operator just defines a path consisting in a number of intermediary manipulator configuration.

These configurations are constructed by moving the arm in the desired area and pressing a switch. The representation of a co-ordinate frame is displayed at the selected location. It features sensitive components (figure 3) that allow the operator to easily modify them both in translation and orientation only with the mouse. When a path has been defined, a trajectory is automatically generated using an automatic collision free trajectory generation algorithm.

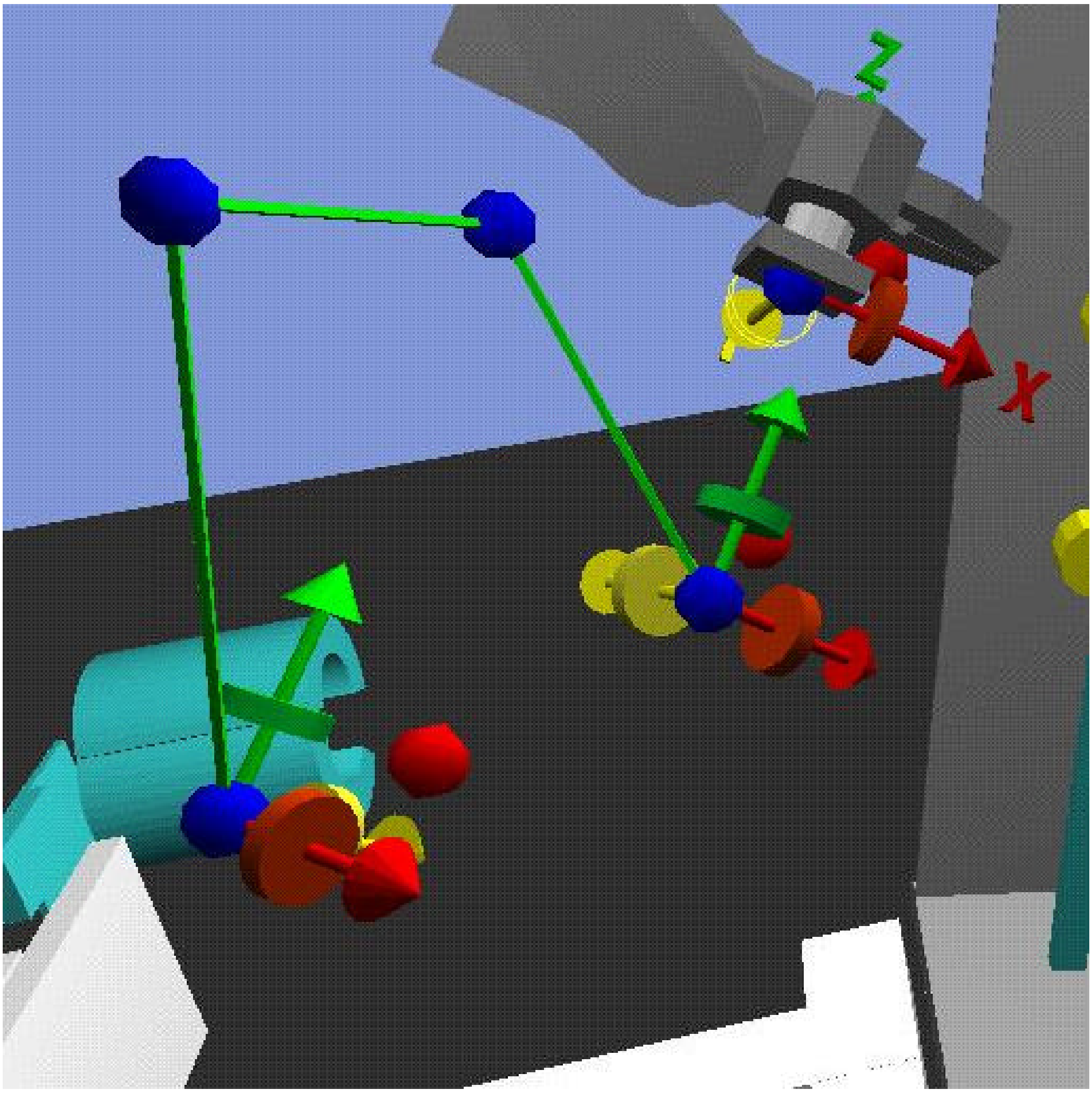

Figure 3 : Creation of a path that can be easily modified

RESULTS

The main benefit of the graphical programming demonstrator is to allow the operator to easily prepare a mission using a representation of the 3D workspace where all the geometrical parameters required by the robot are displayed. Additionally, it provides an efficient means to generate collision free trajectories that can be very complex when the environment is encumbered by obstacles.

The assessment of the system have shown the following advantages :

- robot programming is simplified by relying only on simple input devices (classical 2D mouse and 6 DOF SpaceBall or SpaceMouse) ;

- help messages are displayed for each mouse motion and inform the operator of the commands that are available at any given moment ;

- starting complex robot programs is easily made by designating objects with the mouse inside the 3D environment ; often, geometrical parameters are not requested by the system since they are implicitely defined through the designated environment objects ;

- the configuration of the manipulator is well understood by the operator as it is displayed on the synthetic images and colours are used to indicate mechanical stops or collision threats ;

- the operator may virtually move the arm using the SpaceBall or SpaceMouse and be aware of collisions ;

- all the parameters of the robotics procedures are displayed on the screen.

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