FROM RESEARCH TO INDUSTRY

cea tech

INTERACTIVE ROBOTICS

list

PURESAFE FINAL CONFERENCE

FORCE FEEDBACK NUCLEAR TELEROBOTICS IN FRANCE: R&D RESULTS AND INDUSTRIAL ACHIEVEMENTS

JANUARY 2015 – CERN

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INSTITUT CARNOT CEA LIST

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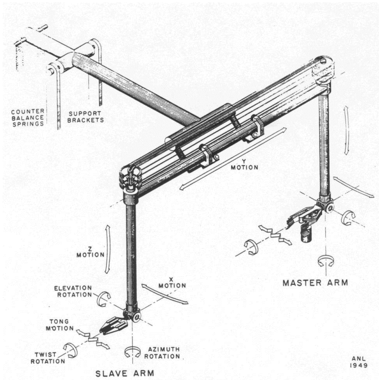
SPECIFICITIES OF THE CONTEXT OF NUCLEAR ROBOTICS IN FRANCE

- France is producing about 80% of its electricity by nuclear power plants (EDF)
- France recycles the nuclear fuel (AREVA) : La Hague plant is the principle user of teleoperation (more than 500 MSM operational)
- The dismantling domain is a major field of application for robotics
- The research and development of nuclear robotics at CEA has been steadily continued in particular with a jointed effort with AREVA
- Significant companies operating in the field of nuclear robotics (Getinge-La Calhène, ECA, Cybernetix, Comex, Haption..)
- The CEA has been continually active in a wide range of related technologies and processes: hardened electronic technologies, gamma camera, sensors, decontamination processes, real time dose rate estimation, communication network
- The CEA Interactive Robotics (LRI) & Interactive Simulation (LSI) Laboratories has been continually supporting the emergency intervention robotic group GIE INTRA (a partner of the similar German group KHG)

FROM MECHANICAL MASTER SLAVE TO COMPUTER ASSISTED TELEOPERATION

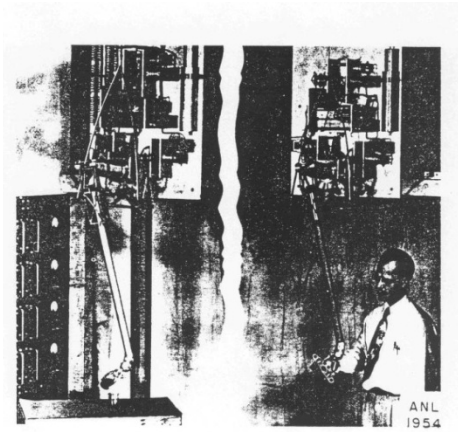
First mechanical (force feedback !) master slave manipulator by Ray Goertz (1948)



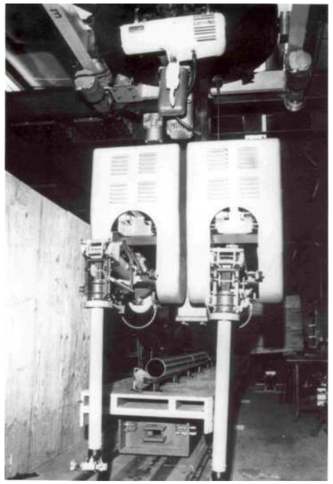
MECHANICAL MASTER-SLAVE MANIPULATOR ANL MODEL 1 (EXPERIMENTAL MODEL)

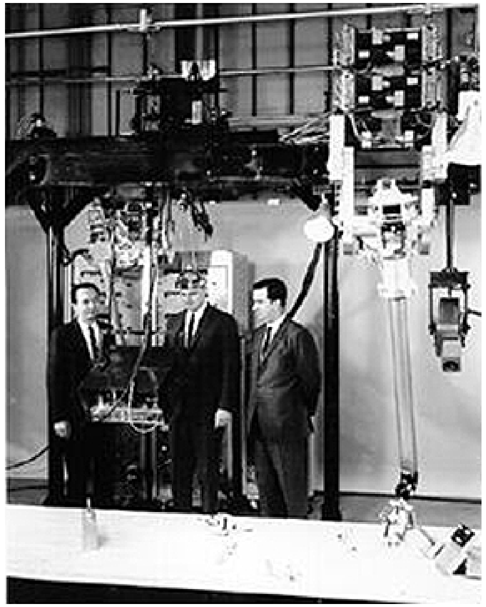
DEVELOPED IN 1948-49 TO EVALUATE THE PRINCIPLES OF MASTER-SLAVE CONCEPTS. NEVER PRODUCED COMMERCIALLY.

First electrical force feedback master slave manipulator by Ray Goertz (1954)



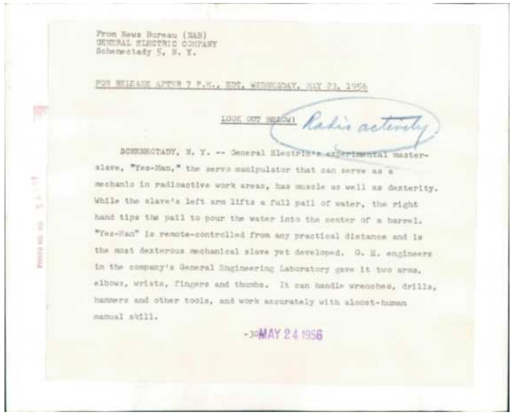
ELECTRIC MASTER-SLAVE MANIPULATOR ANL MODEL 1
DEVELOPED IN 1954 - USED ONLY FOR EXPERIMENTAL PURPOSES.





CRL Model M
at Fermilab

Hydraulic servomanipulators by Ralph Mosher, General Electric



From News Bureau (NAB)
GENERAL ELECTRIC COMPANY
Schenectady 5, N. Y.

FOR RELEASE AFTER 7 P.M., EDT, WEDNESDAY, MAY 23, 1956

LOOK OUT BELOW! Radio activity

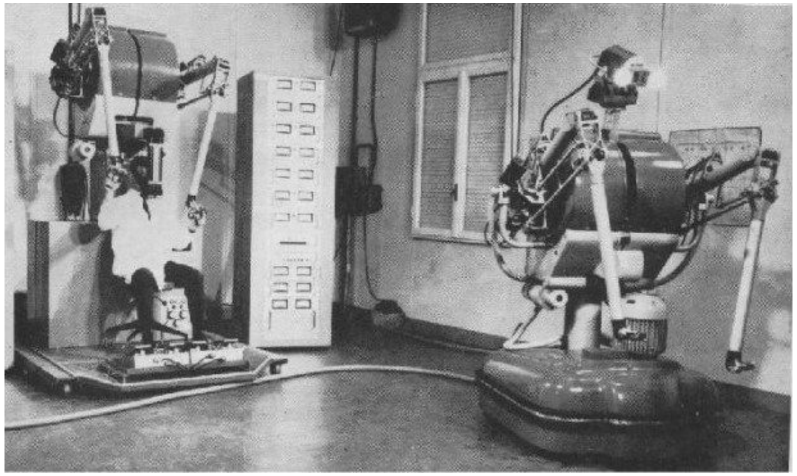
SCHENECTADY, N. Y. -- General Electric's experimental master-slave, "Yes-Man," the servo manipulator that can serve as a mechanic in radioactive work areas, has muscle as well as dexterity. While the slave's left arm lifts a full pail of water, the right hand tips the pail to pour the water into the center of a barrel. "Yes-Man" is remote-controlled from any practical distance and is the most dexterous mechanical slave yet developed. G. E. engineers in the company's General Engineering Laboratory gave it two arms, elbows, wrists, fingers and thumbs. It can handle wrenches, drills, hammers and other tools, and work accurately with almost-human manual skill.

-30- MAY 24 1956

"Yes-Man« (1956)

Hardiman (1958)

1958 – MASCOT (MAnipulatore Servo COntrollato Transistorizzato)
Remote Servo-manipulator – Carlo Mancini (Italian)



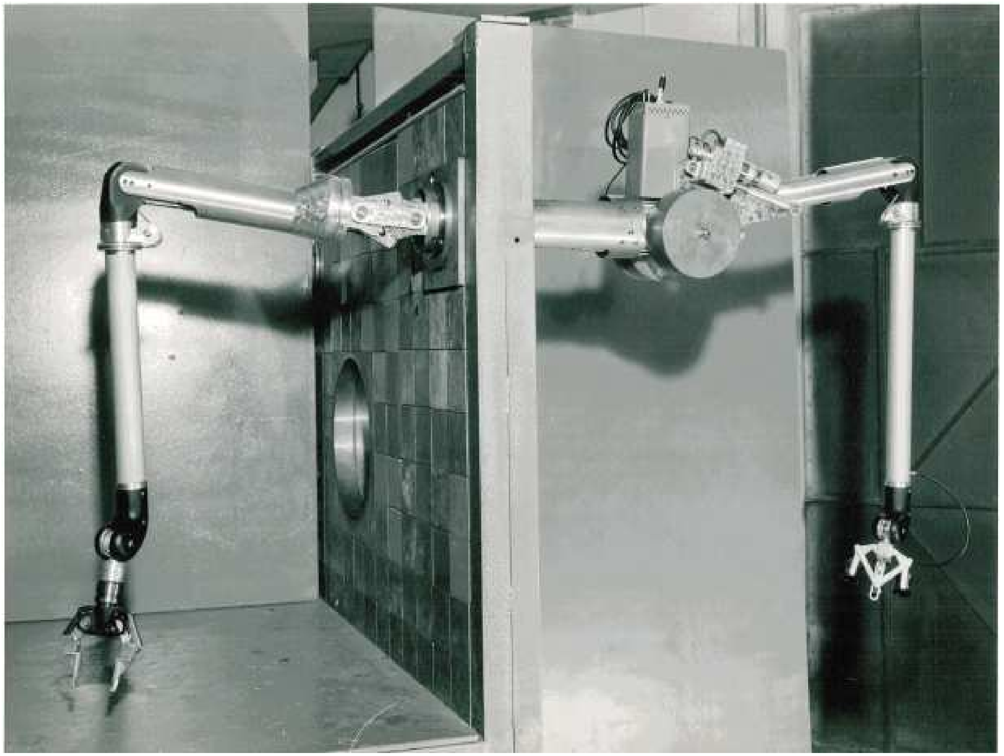
ELECTRONIC EXHIBITION IN ROME – 1962

Figure 9 Mascot operating inside the JET Torus in 1996

MASCOT APPLICATIONS: left CERN (early 70's)➔, right JET (Dexter, 1996)

Articulated mechanical master slave MA11 CEA-La Calhène (1966)

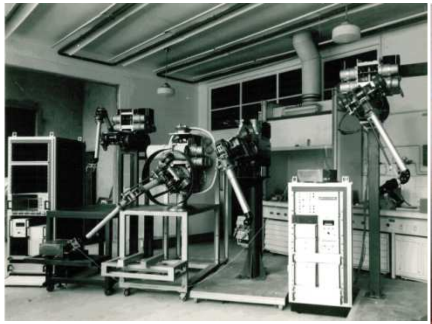
- Original electromechanical offset system for the shoulder (increase the working volume) – Patented by J. Vertut



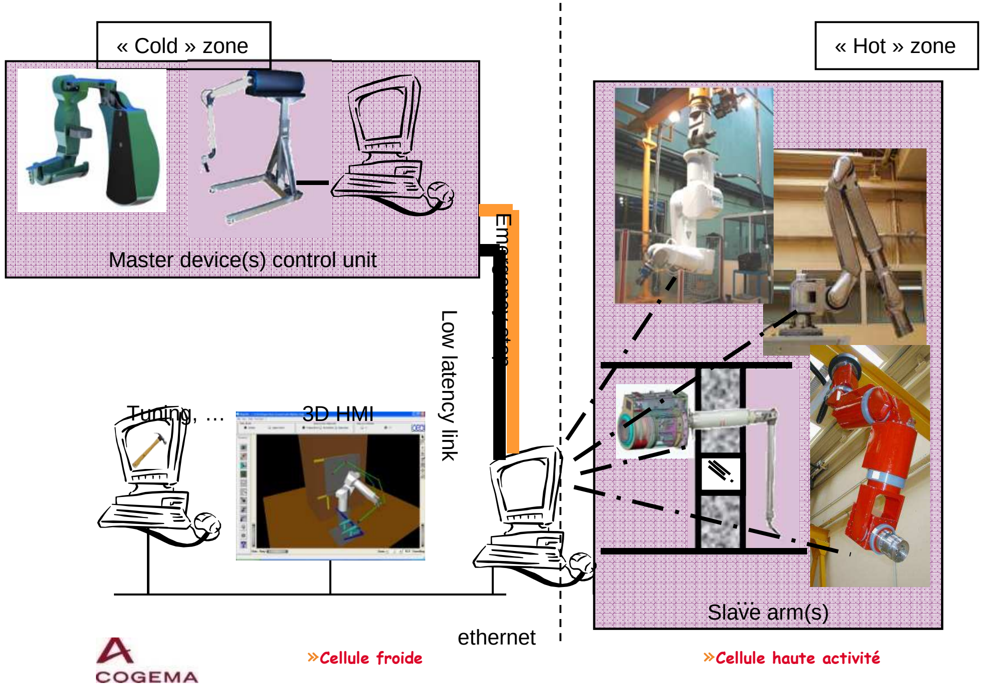
Servo-manipulateur maître-esclave MA23 (1975)

- MA23 including patented original torque amplification mechanism using block and tackle (1974)
- Analogous electronics allowing force feedback teleoperation
- Lately adapted to the first Computer Assisted Teleoperation sofware TAO1 and 2 (>1980)
- Several nuclear applications including:
  - Experimental dismantling tests at the hot-cell AT-1 from COGEMA-Hague (AREVA NC)
  - welding

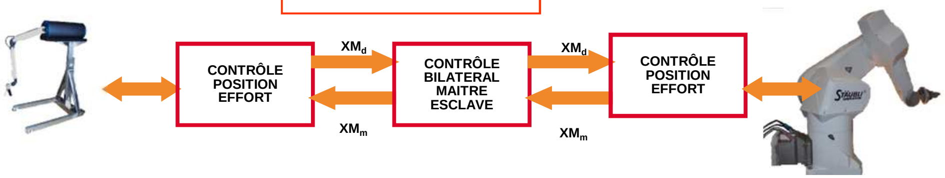
- About 25 units produced to date



Computed Assisted Force Feedback Teleoperation – A flexible system centered around a Cartesian coordinates controller (TAO 2000)

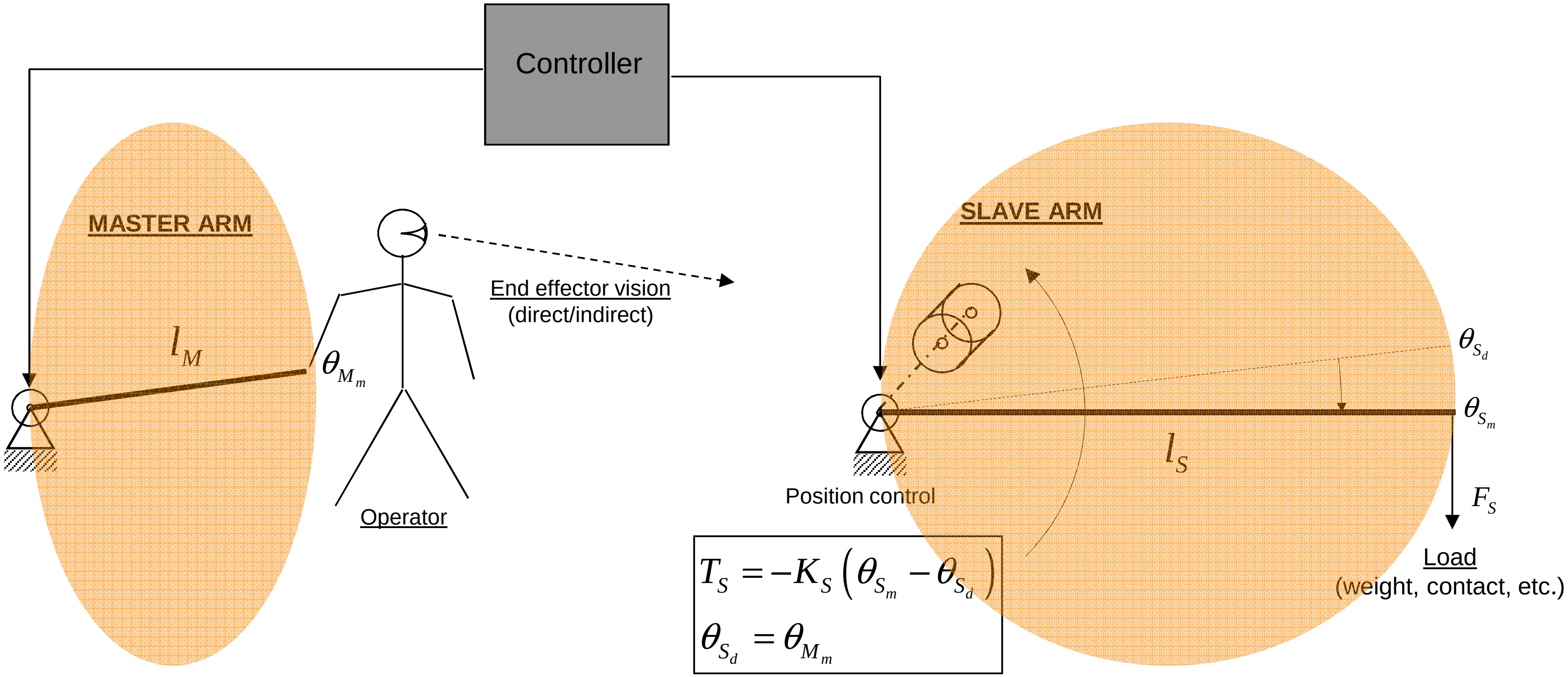


Functional scheme



MASTER-SLAVE MAIN CONCEPTS BASED ON MECHANICAL ANALOGIES

UNILATERAL COUPLING



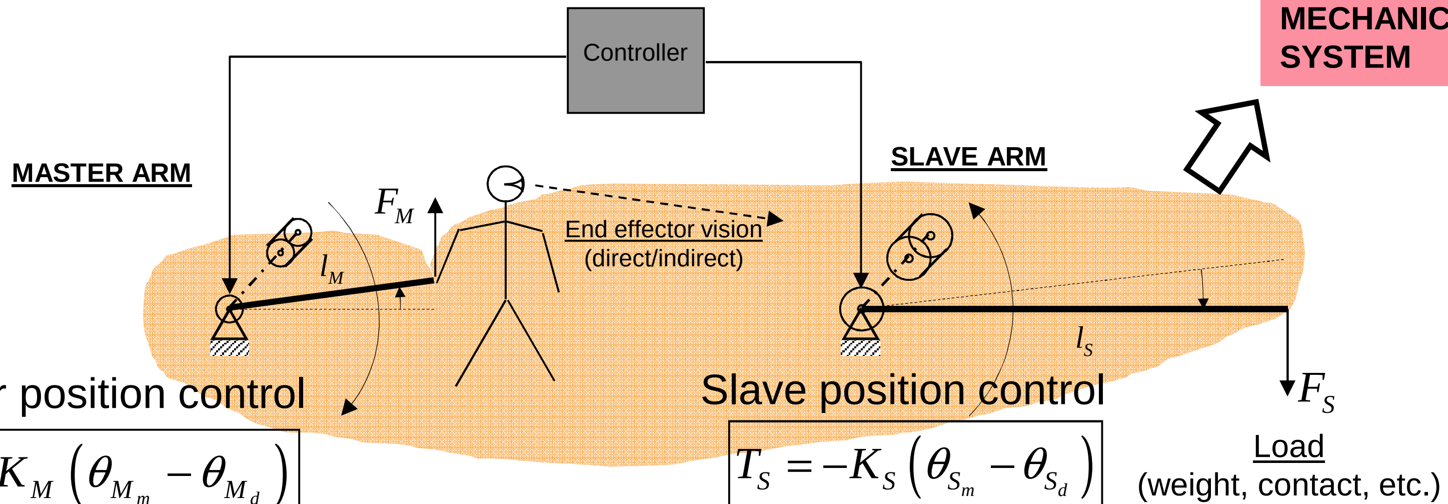
$$T_S = -K_S\left(\theta_{S_m} - \theta_{S_d}\right)$$

$$\theta_{S_d} = \theta_{M_m}$$

MASTER & SLAVE ARE 2 INDEPENDENT MECHANICALSYSTEMS

BILATERAL COUPLING

EXTENDED SINGLE MECHANICAL SYSTEM



Master position control

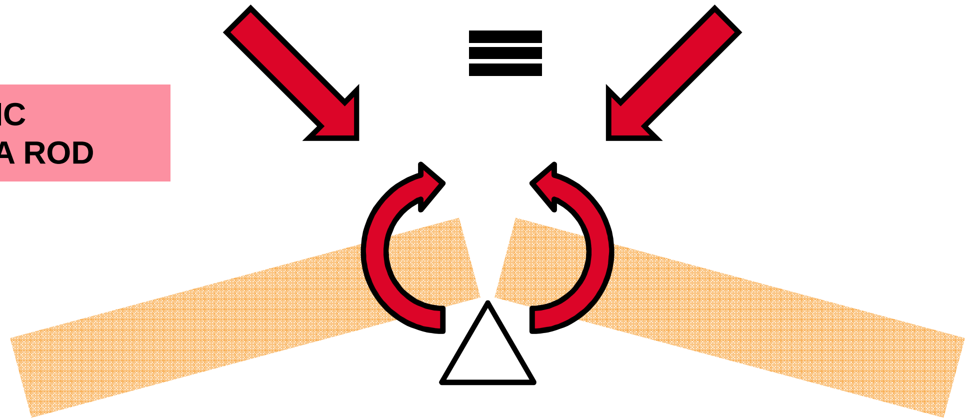
$$T_M = -K_M\left(\theta_{M_m} - \theta_{M_d}\right)$$
$$\theta_{M_d} = \theta_{S_m}$$

Slave position control

$$T_S = -K_S\left(\theta_{S_m} - \theta_{S_d}\right)$$
$$\theta_{S_d} = \theta_{M_m}$$

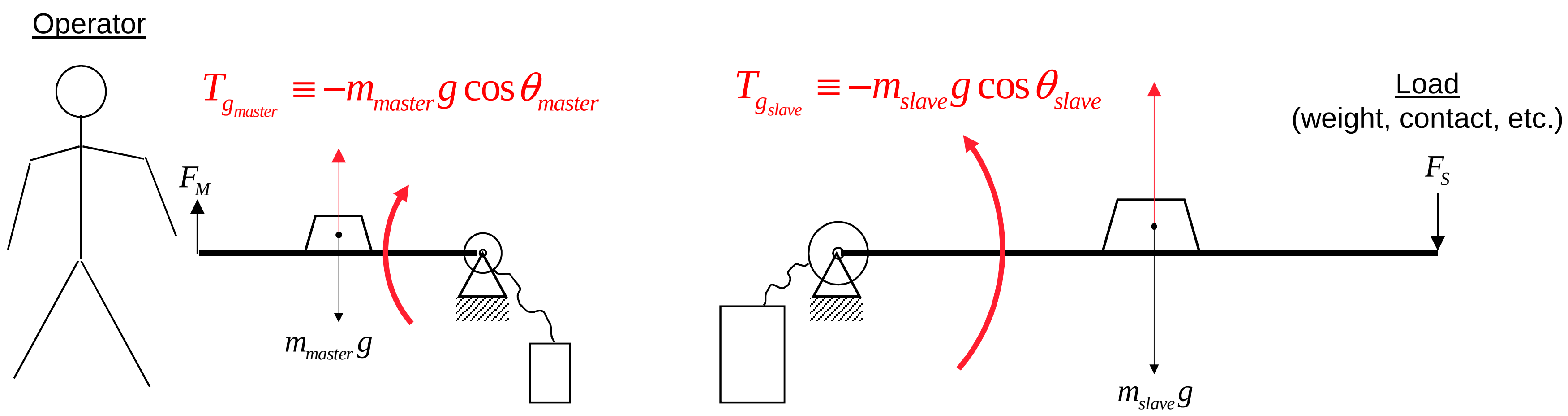
ANALOGY WITH ELASTIC COHESION FORCES IN A ROD

$\equiv$

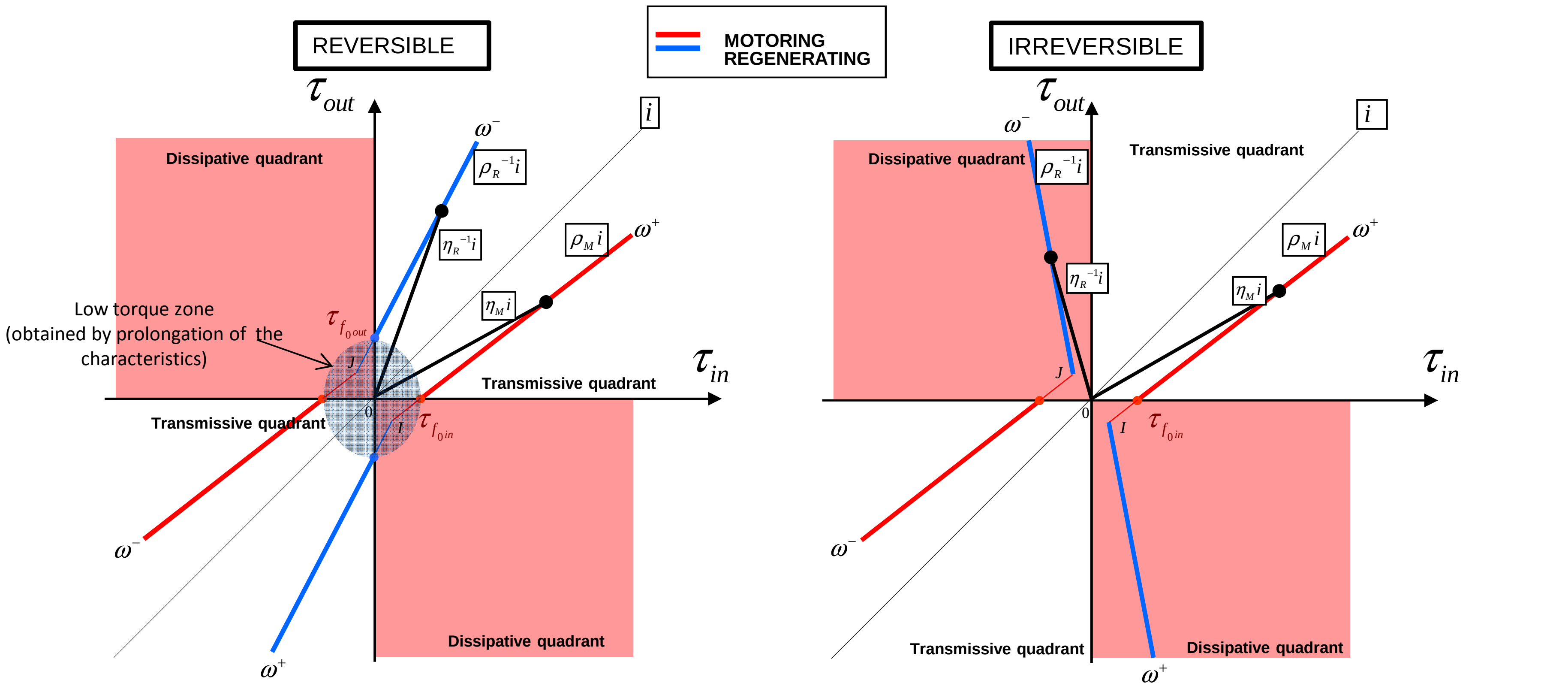


PERFORMANCE IMPROVEMENT 1

STATIC BALANCING



FORCE TRANSFER IN THE ACTUATOR

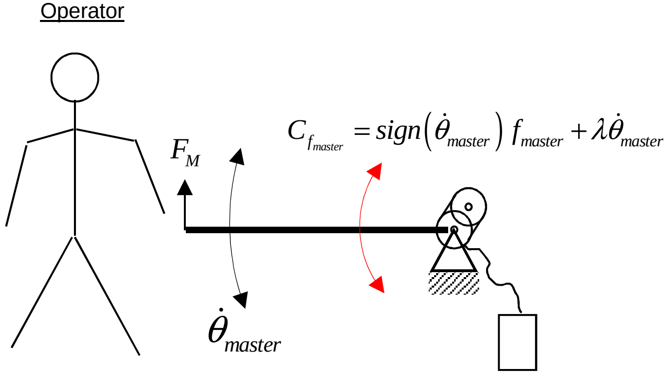


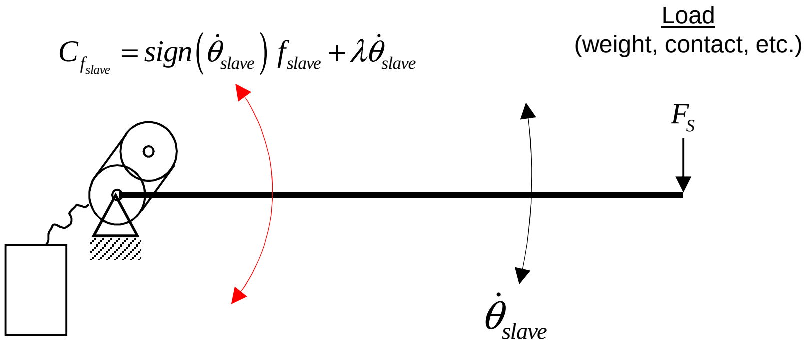
"**Telerobotics research and development at CEA LIST**"
P. Garrec and F. Geffard and O. David and F-X Russotto and Y. Measson and Y. Perrot
ANS EPRRSD - 13th Robotics & remote Systems for Hazardous Environments • 11th Emergency Preparedness & Response - Knoxville, TN, August 7-10, 2011

"Dry friction modeling in dynamic identification for robot manipulators: Theory and experiments,"
Kammerer, N.; Garrec, P.,
Mechatronics (ICM), 2013 IEEE International Conference

PERFORMANCE IMPROVEMENT 2

FRICTION COMPENSATION

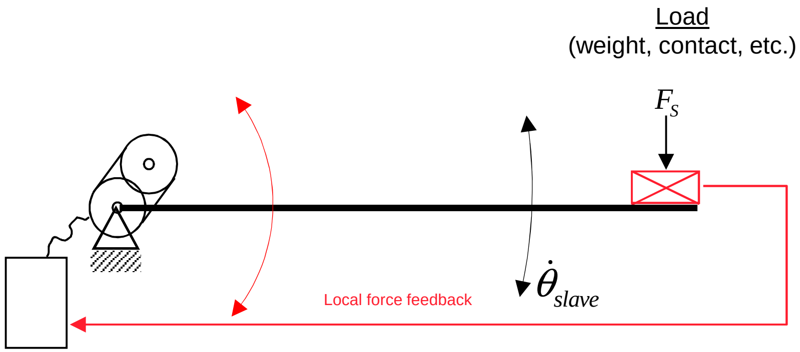




$T_{f_{master}} = sign(\dot{\theta}_{master})\, f_{master} + \lambda \dot{\theta}_{master}$

$T_{f_{slave}} = sign(\dot{\theta}_{slave})\, f_{slave} + \lambda \dot{\theta}_{slave}$

Model based friction compensation (torque linearization)



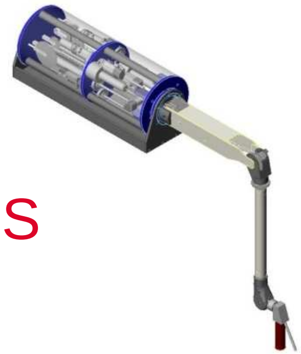
Active closed loop friction compensation (torque linearization)

BACKDRIVABILITY VERSUS REVERSIBILITY (MECHANICAL PROPERTY)

Mechanical type (constructive property)	Behaviour	
Reversible	Backdrivable	
Irreversible	Self-locking	Backdrivable if assisted (force closed loop)

INDUSTRIAL ACHIEVEMENTS OF COMPUTER ASSISTED TELEOPERATION IN FRANCE

FORCE FEEDBACK MASTER ARMS



Virtuose 6D / MAT6D

- Virtuose 6D / MAT6D for teleoperation (2001) ➔ replacing the MA23 (La Calhène)
  - First arm using ball-screw and cable for torque amplification (patented)
  - Used in CEA's laboratories and at AREVA a Hague plant (RX TAO et MT200 TAO)
- Virtuose 6D Haptic (2002)
  - Torque amplification by capstan or Harmonic Drive
  - Sold worldwide
  - Used by major industrials
- All products industrialized and commercialized by HAPTION™

Virtuose 6D Haptic

- Maintenance operations – RX TAO
  - Industrial Stäubli RX robot adapted for force feedback teleoperation (hardened sensor and multiplexer)
  - 5 major interventions since 2005 in La Hague (dissolver wheel)

« TAO2000 V2 computer-assisted force feedback telemanipulators used as maintenance and production tools at the AREVA NC–La Hague fuel recycling plant »
Franck Geffard1, Philippe Garrec1, Gérard Piolain2, Marie-Anne Brudieu3, Jean-François Thro3, Alain Coudray4 and Eric Lelann4,
Journal of Field Robotics, Special Issue: Applied Robotics for the Power Industry, Volume 29, Issue 1, pages 161–174, January/February 2012

Dismantling – MAESTRO TAO

- Specifically developed 100kg payload hydraulic force feedback telerobot by CEA and IFREMER
- Industrialization with Cybernetix
- Applications in dismantling CEA’s laboratories (ongoing)

DISMANTLING WITH THE HYDRAULIC FORCE FEEDBACK TELEROBOT MAESTRO
Y. Méasson, O. David, F.X. Russotto (CEA LIST), J.M. Idasiak (CEA, DEN), L. Facheris (Cybernétix)
ANS EPRRSD - 13th Robotics & remote Systems for Hazardous Environments • 11th Emergency Preparedness & Response - Knoxville, TN, August 7-10, 2011

Hot-cell telescopic teleoperator MT200 TAO

- **An ambitious tight pluri-annual collaboration between the R&D (CEA) and the user (AREVA – La Hague)**
- System replacing a standard telescopic mechanical master slave (4 m extension ; 20 kg capacity)
- Slave actuator unit with force-vented motors (high transparency without force sensor)
- Master arm Virtuose 6D
- TAO 2000 software : bilateral coupling, virtual guides, automatic robotic modes
- **10 months of usage on a vitrification hot-cell (without failure)**
- Broad and immediate acceptance by a majority of plant's operators (including the Cartesian control) ; Intuitive, « one push button » indexing
- **An industrial product in 2014 (Getinge-La Calhène) -**
- **First CAT system able to successfully replace a telescopic MSM**

2004 - CEA

2012 – AREVA cold

2012 – AREVA hot-cell

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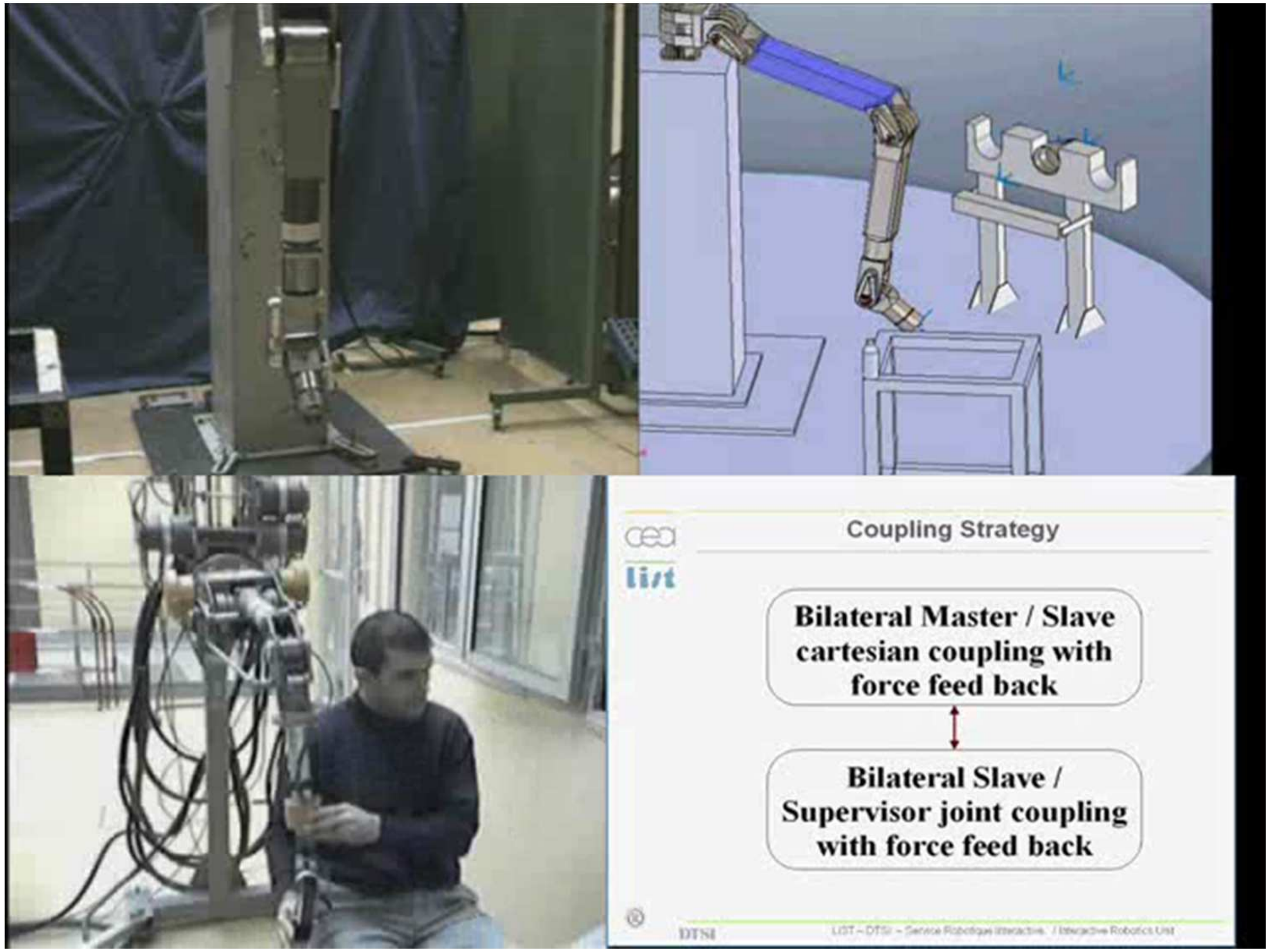
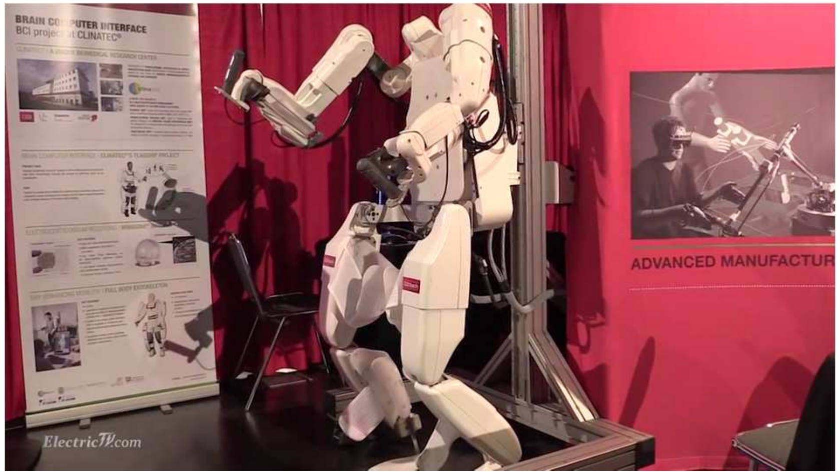
R&D RESULTS

SUPERVISED TRI-AGENTS ADVANCED CONTROL



ADVANCED HAPTICS /TELOPERATION USING THE ARM EXOSKELETON ABLE 7D (INTEGRALLY ACTUATED BY SCREW AND CABLE)



INVITED AT THE SIGGRAPH JULY 2013 – ANAHEIM (USA)

ABLE 7D is commercialized by HAPTION™

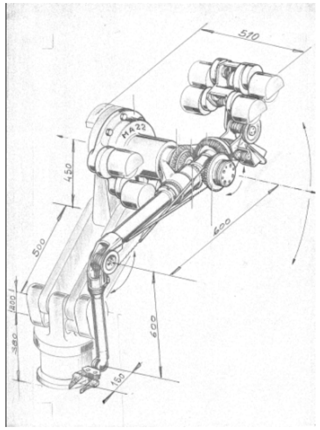
TELEOPERATION WITH MOBILE CARRIER:

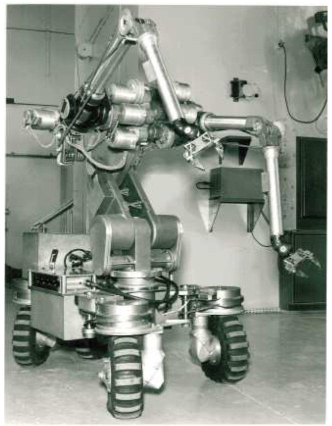
- PROMISING RESULTS FROM THE PAST
- TOO FEW INDUSTRIAL ACHIEVEMENTS..

Mobile twin servomanipulators VIRGULE - MA22 (1972)

- Analogous electronics allowing force feedback teleoperation
- Original high mobility vehicle designed by J. Vertut
- Servo-manipulator MA22: a jointed design by J. Vertut (CEA) and Carl Flatau (Brookhaven Lab.)
- Rare earth DC torque motors

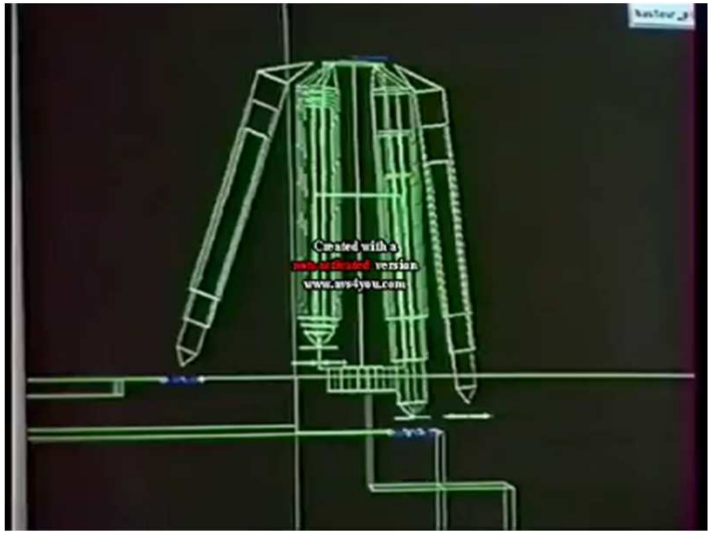
Jean VERTUT



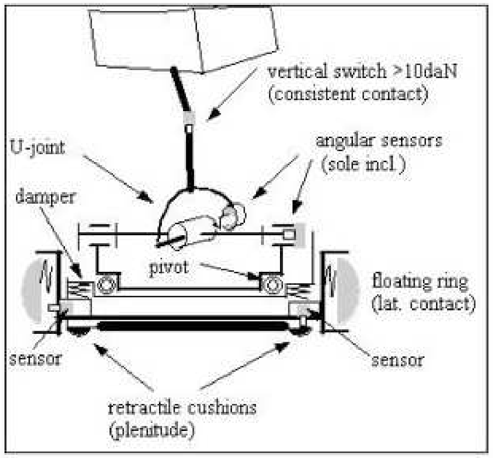


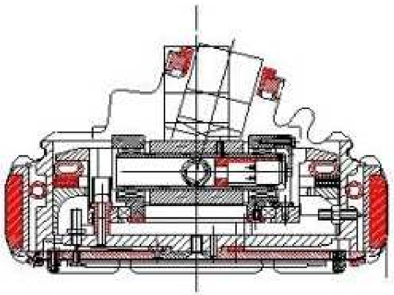
SHERPA – Hexapod transporter (European TELEMAN program)

- Based on the hexapod telescopic legged transporter Odex 3 (Odetics, USA)
- Original tactile feet (CEA patent)
- Original algorithms for stair climbing and obstacle avoidance using reflex reactions
- First legged robot to be demonstrated in nuclear plants
- Transport of 200 kg on stairs in « loose » teleoperation (EDF Chooz-B, France in 1993 and ENEL Trino in 1994)



CEA Fontenay-aux-Roses laboratory (early 1993)



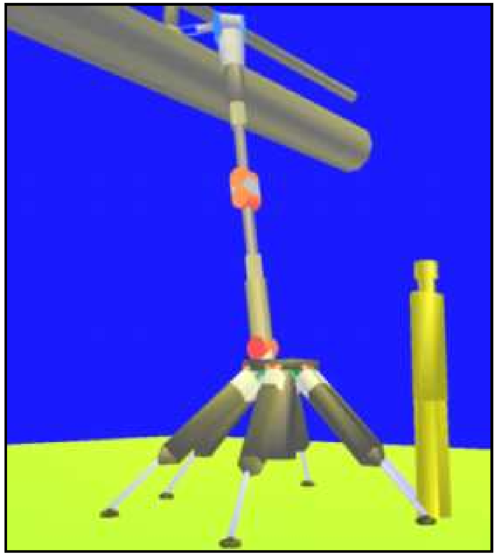


EDF- PWR CHOOZ B - 1993

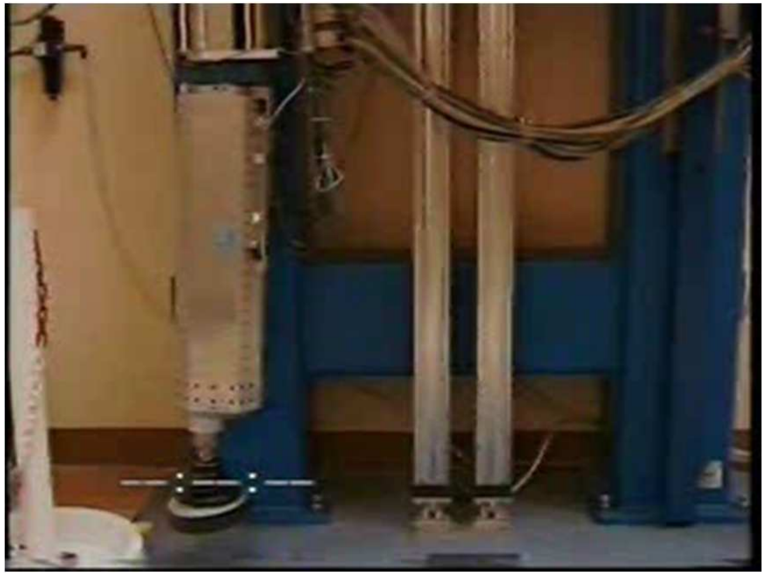
EXTENSIVE FIELD TESTS IN TWO NUCLEAR POWER PLANTS (1993 – 1994)

ENEL PWR TRINO - 1994

SHERPA 2 projet (CEA-EDF-TECHNICATOME) ➔1994-1998



- A compact hexapod (55cm width) able to transport 300 kg
- Deployment of a power foldable arm carrier
- Use of a compact industrial arm as a tool (Mitsubishi PA10)
- New telescopic leg mechanical design (patents)ouvelle technologie de jambe compacte et modulaire
- Bras porteur modulaire redondant (contournement des obstacles)
- Emport d'un outil de manipulation secondaire
- Technologie en partie exploitée sur le robot de maintenance de la chambre d'expérimentation du LMJ



DEXTROUS – LONG REACH MANIPULATORS FOR LARGE SCIENTIFIC FACILITIES

LONG REACH MANIPULATORS

- Long reach articulated arm (AIA)
  - CEA LIST design and developement (since 1995)
  - First introduction in the TORE SUPRA tokamak achieved in 2008 (restart of the installation the next day without « braking » the vacuum)
  - Applications forecasted at AREVA's La Hague recycling plant

- Long reach telescopic arm
  - LMJ (Mega-Joule Laser) maintenance manipulator
  - Original design by CEA LIST (2004-2008) for the CEA DAM (CEA defence division) based on CEA LIST patents (➔Sherpa 2 project)
  - Industrialization by Cybernetix in collaboration with CEA LIST
  - Operational (automatic plug-in of protective panels) in 2012

Multi-limb articulated carrier AIA

Real field test in the tokamak TORE SUPRA (2008)
Operated at 120℃ (200℃ for degasing) and 10-5 Pa
Applications in tokamak and hot-cells (undergoing)

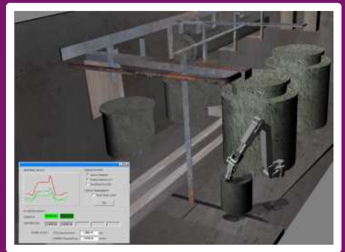
Long reach telescopic arm for the LMJ (Mega-Joule Laser)

- 100kg payload
- 12 m horizontal ext.
- 0,63m port diameter
- Collapses in a 6m mobile casing
- Centimetric hysteresis thanks to hyperstatic lighweight telescopic structure (high repeatability)
- Plug-in/out panels (50kg) automatically exploiting manipulator’s compliance

THE PRECIOUS BENEFITS OF INTERACTIVE SIMULATION

Dismantling Life Cycle :

To simulation, from concept up to task completion

Preparation of the mission	Simulation of the scenario	Execution
Scenario definition on the digital mock up	Scenario qualification Operator training	Supervision and operator assistance
		
Accessibility studies, dose rate evaluat°, task définit° kinematics optimization	Real-time simulation with haptics, interactive training	Operator assistance and scenario Execution Same content, context, and tools

EURIWARE

OREKA SUD

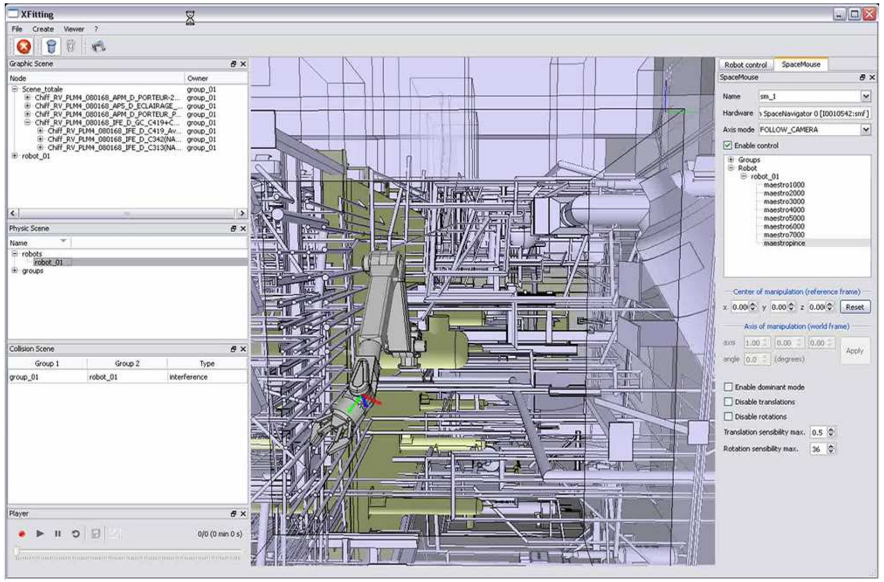
haption

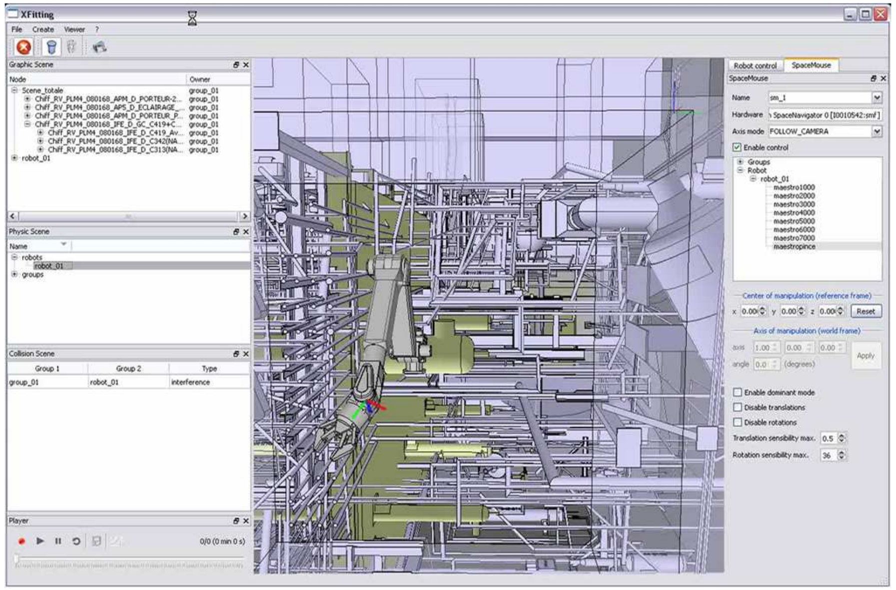
cybernétix

VIRTUAL REALITY & INTERACTIVE SIMULATION WORKS

- Virtual prototyping : accessibility studies, assembly/disassembly on digital mock-up
- Ergonomy studies : musculo-skeleton disorders diagnosis, task optimization
- Robotics simulation / supervision : intervention scenario, assistance to cobotic solution design
- Training of the operators

REAL-TIME MULTI-PHYSICS xde *SOFTWARE* (*EXTENDED DYNAMIC ENGINE*)





RAD HARD ELECTRONICS

- An activity created in 1988, 2 years after Chernobyl accident, to study the feasibility of designing and realizing highly radiation hardened electronic systems
  - 25 years experience in this field !
  - Mainly use of COTS (Components Off The Shelf)
  - Many industrial cooperation in this domain (IRSN, EDF, AREVA, INTRA)
  - Several Rad-Hard systems were designed and prototyped, some of them are used in EDF NPP and AREVA La Hague decommissioning plant
- Use of our own efficient design methodology
  - Based on theoretical and experimental knowledge of the effects of radiations on COTS
  - Real environment tests for qualification
  - Pre industrial series

HARDENING OF ELECTRONIC SYSTEMS

Hardening at system level

- Shielding: lead (γ rays), hydrogenated materials (neutrons)
- → **Specific architecture: redundancy, error correction, safe mode, reboot**
- → **Correction by software: extra instructions for error detection and correction**

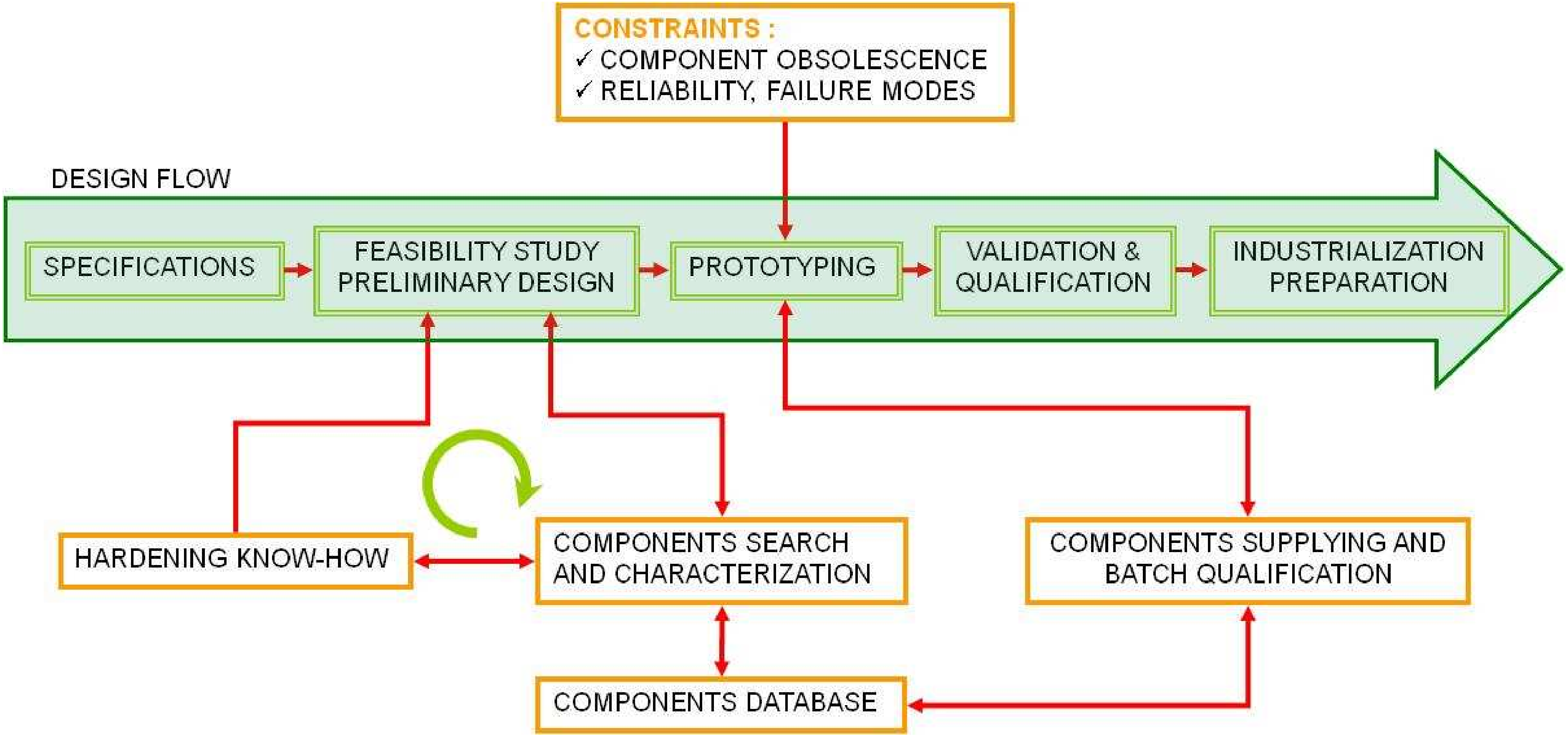
Hardening at sub-assembly level

- → **Component selection: rad-hard parts or qualification of COTS by lot**
- → **Design of modules: compensation of radiation effects; tolerance to perturbations**
- Shielding: components or modules

Hardening at component level (design of ASIC)

- → **Component regeneration for enhanced radiation tolerance and longer lifetime**
- Hardened technology: hardness assurance provided by manufacturer; specific libraries
- CMOS commercial technology: use of special design rules (enclosed transistors); Insulating layers (SOI, epi-layer); hardened functions library

COTS-BASED DESIGN METHODOLOGY FOR RADIATION HARDENING



RADIATION HARDENED ELECTRONICS FOR TELE-ROBOTICS

Full response for targeted systems

- In/Out-doors mobile robots
- In/Out-doors cranes
- Inspection tools
- Electric or hydraulic manipulators

Validation for radioactive environments

- From 1 kGy to 100 kGy
- Fault-tolerance

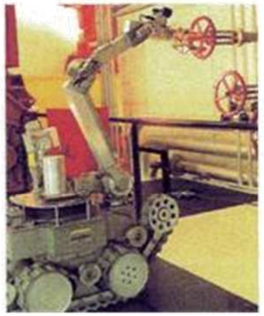
On sites since 1992

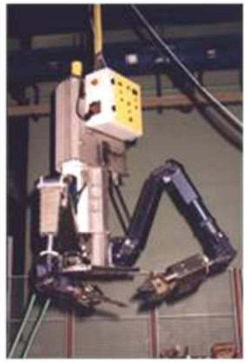
- Up-grading with recent electronic technologie
- Hardening to specific environments (temperature, neutrons)
- Adaptation to existing or new equipments (traveling cranes, cutting and soldering tools, ….)

1 to 10kGy tolerant computer systems

Outdoor robots

Inspection Robot





Hydraulic Manipulator

In-door cranes

COTS-based embedded electronic modules

POWER AMPLIFICATION

Hardened to 10 kGy

- Using COTS components
- MOS, “CoolMOS” or IGBT components

Compensation using threshold voltage drift control

- Usual command laws
- PWM
- Flux vector, V/F controls

Targeted applications

- Control of remote handling engines

Power amplifier for DC Motor

Power amplifier for brushless motor

Power amplifier for induction motor

HIGH DOSE ABSOLUTE POSITION ENCODER

Objectives:

- Increase absolute position measurement precision for radioactive decay cells (reprocessing plant in La Hague) – using COTS

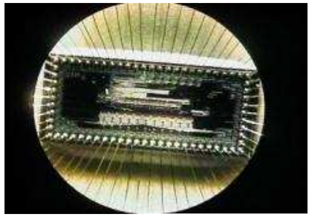
Constraints:

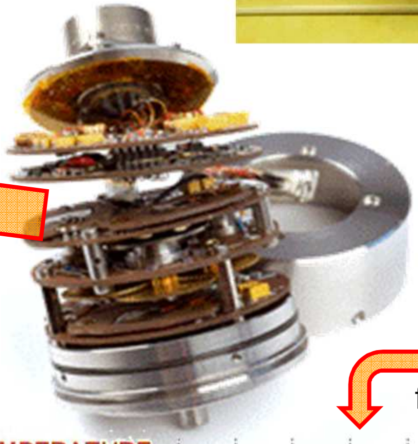
- 2 MGy, Temp. up to 80℃, CEM and vibrations
- Improved an existing encoder (24 bits, 3000tr/mn)

Hardening process:

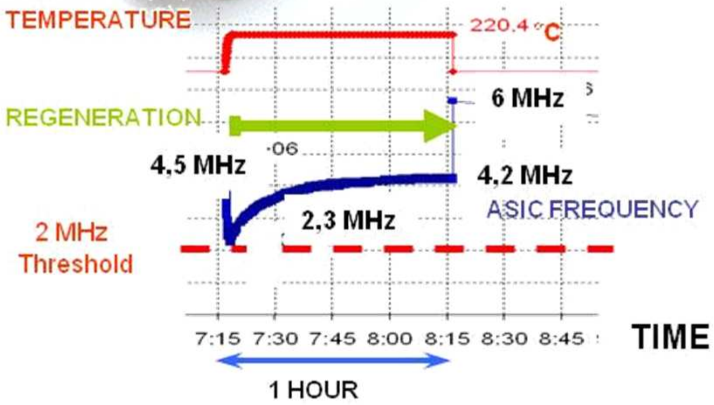
- Identification of key functions, such as optoelectronics, supply, liaisons, internal management
- ASIC in DMILL rad-hard technology : happened to be the weak point of the device
- This high dose level was obtained using specific regeneration properties of electronic technology
- Thermal regeneration during operation

DMILL ASIC





Effects of thermal annealing on ASIC frequency drift control



HIGH DOSE INSPECTION CAMERA

Objectives

- Design of a low cost hardened camera using CMOS image sensor

Constraints

- Up to 50 kGy, 80℃

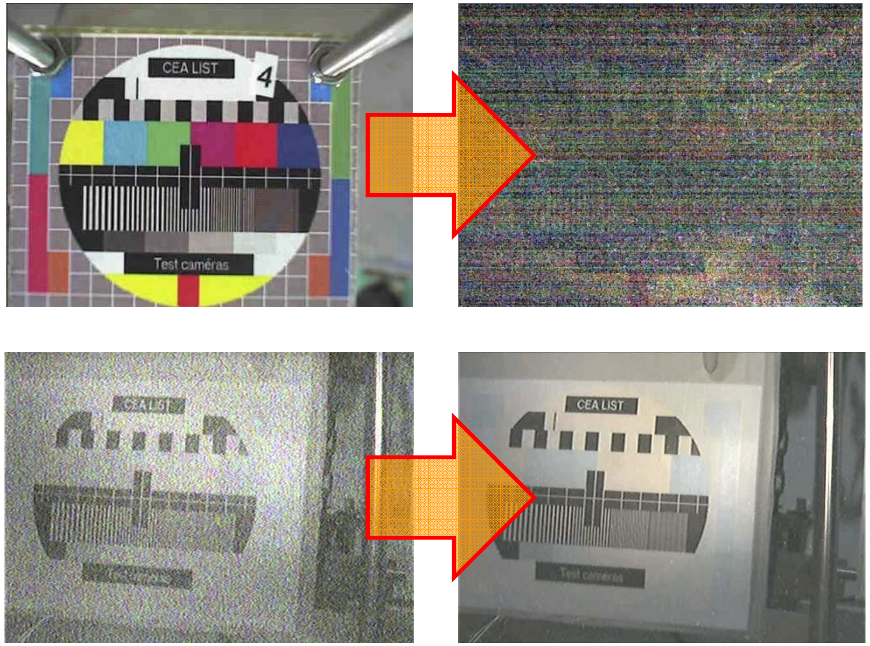
Hardening process

- Selection and tests of COTS CMOS sensors → dead after 5 kGy
- Study of thermal regeneration of the sensor under radiation
- Sensors lifetime extended to more than 150 kGy

Image after 4.5 kGy

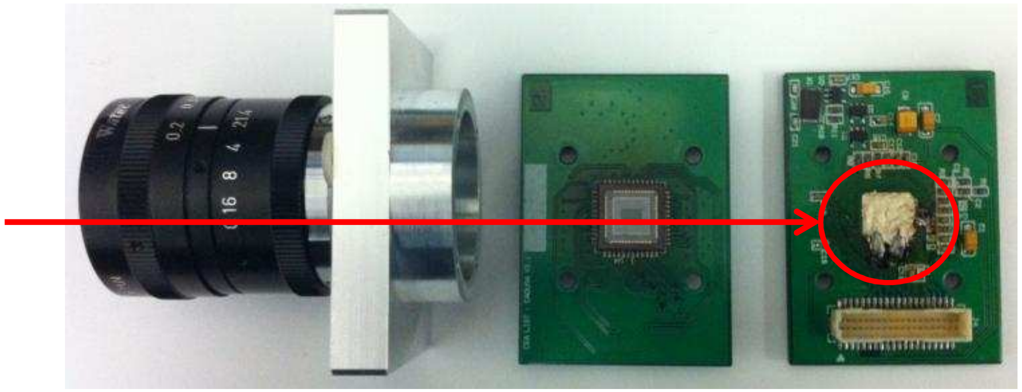
“Normal” sensor

“Regen.” sensor @ **75 kGy**



Before regeneration

After regeneration

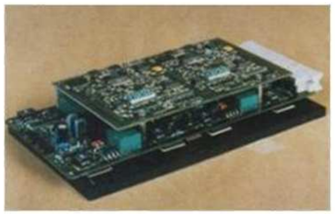


COMPLEX ELECTRONIC SYSTEM HARDENING

CONTROL

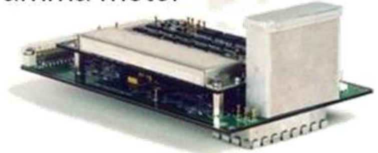

MICADO : Hardened embedded computer


Rad hard supply


Current variator

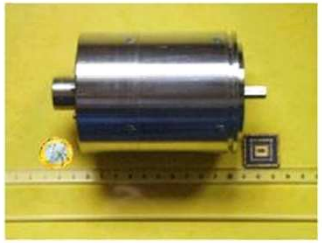
INDOOR CRANE
HARDENED EQUIPMENT

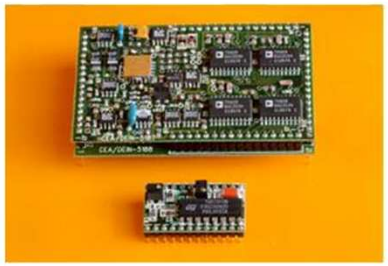
Gamma meter



DATA ACQUISITION


Hardened inspection camera


Absolute position encoder

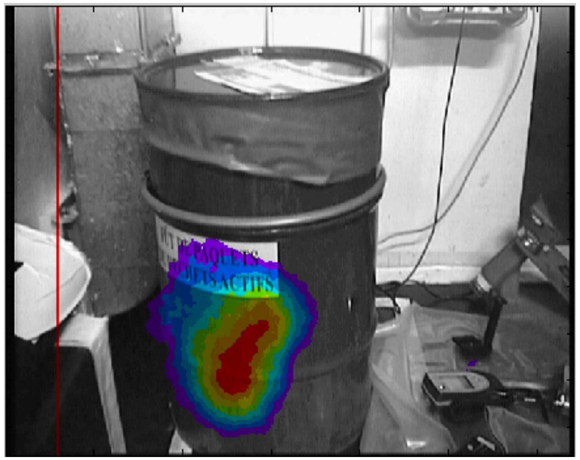

Hardened converter

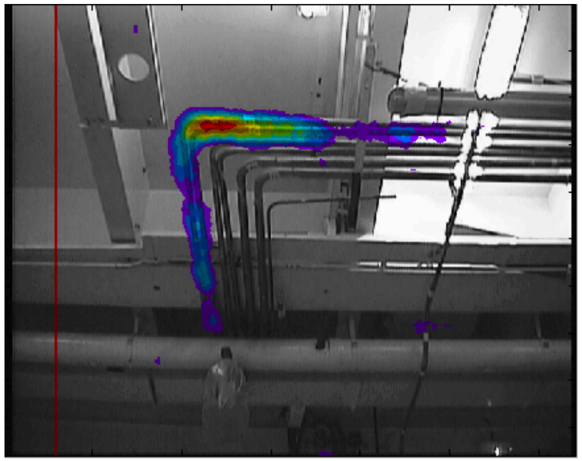
GAMMA CAMERA

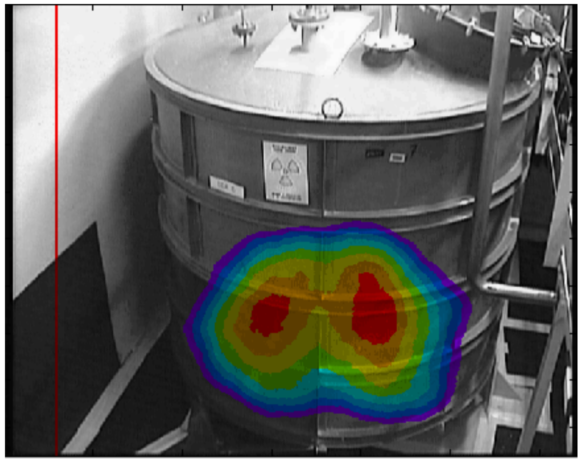
- Ipix

CANBERRA

Pictures of dismantling case (pipe cluster) and in searching sources in barrels





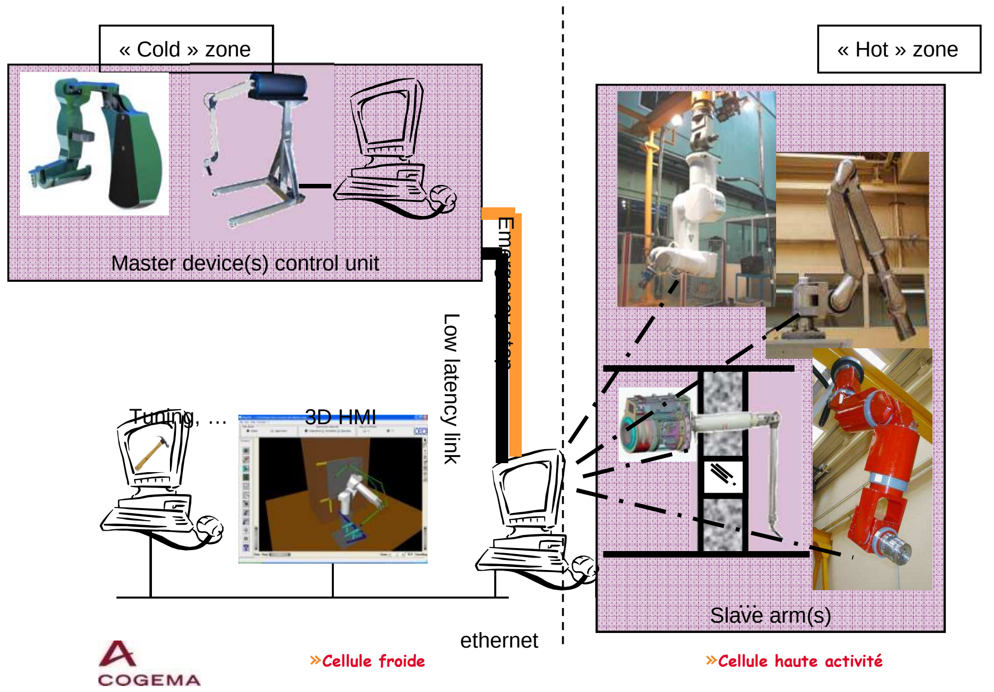


TELEROBOTICS INTEROPERABILITY & STANDARDIZATION

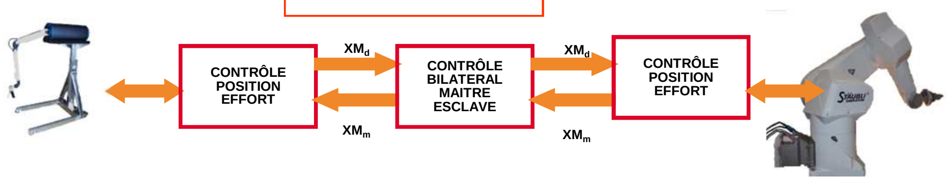
ISO - TC85 - SC2
WG 24 - Remote handling devices for radioactive materials

- <u>PWI 16660 - Telerobotics Systems for Nuclear Applications</u>

Examples of up-to-date telerobotics systems



Functional scheme



ISO-TC85-SC2-WG 24 - Remote handling devices for radioactive materials

PWI 16660 Telerobotics project

WHY DEVELOPPING A TELEROBOTIC/TELEOPERATION STANDARD ?

- Computer assisted telerobotics has reached an industrial maturity (TRL9 on 3 systems in France in AREVA/CEA nuclear installations)
- Force feedback telerobot have been found more productive and reliable than a conventional mechanical master-slave (AREVA-CEA publication in 2012)
- Telerobotics will be necessary in glove boxes
- AREVA and ITER are supporting a standard for the following reasons: maintainability/ evolutivity/perenity/safety/quality control as well as to optimize processes and plant design
- Post-accidental intervention group KHG is supporting a standard for inter-communication and interoperability.

OTHER POSITIVE CONSEQUENCES OF A STANDARD:

- Increase component quality by setting the conditions for a sound competition between suppliers
- Facilitates using interactive simulation (haptic VR) as a tool for training/task preparation/supervision
- Inspire a new dynamics by re-linking nuclear telerobotics with other fields (telesurgery, spatial, haptics) and with the academic robotic

CONCLUSION

- Force feedback computer assisted teleoperation is today operational at an industrial level in France (TRL9)
  - A single multi-purpose controller working in cartesian coordinates
  - Several target slave from dismantling to maintenance (hydraulic and electric actuator)
  - Hardened electronics to face high radiation level
  - First telescopic telerobot replacing a conventional mechanical master slave for production work (recycling plant)
  - Refined haptic interface
  - Applied mission planning using VR and haptics
- Promising R&D results for the man-machine interface
  - Force feedback teleoperation with a 7dof exoskeleton master
  - Advanced supervision control using interactive simulation
- Large scale long reach manipulators deployment for the maintenance of large scientific equipments : Tore Supra (1998) and Laser Mega-Joule (2012)
- Dismantling industry is a prime opportunity to develop telerobotics (in particular to face Fukushima’s challenges) – More efforts needed for mobile telerobotics

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