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Human-centered Design of an Interactive Industrial Robot System Through Participative Simulations: Application to a Pyrotechnic Tank Cleaning Workstation

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Abstract— **Industrials are starting to deploy collaborative robots as new solutions to improve workstations. In particular workstations where human operators may get injured because of repetitive tasks, bad postures or heavy loads are targeted. Collaborative robots can also be an alternative to robots which may take up too much floor space with their safeguards or are not flexible and smart enough to handle complex operations. The introduction of such interactive systems on industrial workstations must satisfy the following requirements: ergonomics and safety of the system, quality and performance of operations, and human well-being. We propose a human-centered approach to improve the introduction of collaborative robots in the industry. Several industrial applications are studied within Safran and Airbus Safran Launchers. In this paper, we present the first application of our work on a pyrotechnic tank cleaning workstation. Our approach is illustrated with the design of a solution through several simulation steps involving the workstation's operators. In particular, the current design of a prototype based on a teleoperated robot is introduced.**

I. INTRODUCTION

A. Context

The word "cobot" was introduced in 1996 by Colgate & Peshkin [1] as a particular passive device collaborating with a human operator to accomplish a manipulation task and which can guide and constrain human motion with virtual surfaces. The definition of cobots has evolved since then and they are now generally referred as robots with the ability to collaborate physically with humans in a shared workspace.

Its only since 2008, that collaborative robots (or cobots) started to come out in the industry with Universal Robots' UR5. They were joined after 2011 by RB3D, Rethink Robotics' Baxter, and Kuka's LBR iiwa. Nowadays, most major robot manufacturers have released their cobot.

In France, major industrial groups such as Safran, Groupe PSA, Dassault Systemes, Actemium and Airbus, and institutes such as CEA (French Alternative Energies and Atomic Energy Commission), Cetim (The French Technical centre for mechanical industry), LAAS-CNRS and Art et Metiers participate in the development of collaborative robotics, with initiatives like FactoryLab or the ICARO project.

More and more collaborative applications are deployed in the industry. They require new protective measures to ensure the operator's safety during collaborative operation. Work has been done on this subject recently with ISO/TS 15066 for collaborative robot system safety [2]. The development of these collaborative applications should also be guided to ensure performance and ergonomics of operations and of human-robot interactions on industrial workstation. Little work has been done in this respect. There is a need for a methodology to help in the successful introduction of these new interactive robot systems on industrial workstations.

This need was illustrated in Safran in 2012. The first collaborative robot was introduced in the group and aimed at improving work conditions on a workstation. The cobot's added value was to reduce the weight of products carried by operators and to provide virtual guides for the operations. Unfortunately, the cobot could not handle every type of product transformed on this workstation and operators had trouble using virtual guides. Operators' interview revealed a level of satisfaction that can be improved and a diminution of operations' performance. A brief analysis of work activity driving the design of the system had been done by the cobot integrator with insufficient care about industrial and operators' variabilities. Moreover, operators' needs had not been included during the design of the system and insufficient time had been taken for operators training and system qualification. Other occurrences of such issues in the industry have been reported and analysed more recently [3].

Facing the emergence of this new technology with a high potential to improve industrial workstation ergonomics and lessons learned from the past, the decision was taken at Safran to develop expertise on the study and integration of collaborative robots. Safran being an international group, a formalized and methodical approach was needed to be applied to a wide range of industrial projects in its various subsidiaries. The "Cobotics project" (for collaborative robotics) was launched within Safran, to enhance future introduction of collaborative robots on workstations, especially in terms of:

- performance of operations and of human-robot interactions;
- improvement of work conditions;
- complementarity with operators expertise;
- adaptation to operators, workstation and product variabilities;
- change management and appropriation of the system by the operators.

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B. Contribution

To answer this need of a methodology for the introduction of collaborative robots in the industry, we used an interdisciplinary approach inspired from ergonomics and robotics. On one hand, robotics discipline has dominated the study and the design of robots and human-robot interactions [4]. On the other hand, ergonomics has developed for decades approaches to support industrial design projects [5]. In particular, ergonomists have demonstrated the benefits of incorporating real work activity constraints and involving operators in this design.

The arrival of collaborative robots rise new issues, especially regarding safety, due to human-robot proximity on industrial workstations. However, as other interactive robot systems, their study concern robot system design, human factors and ergonomics, level of automation [6], interface design, and more broadly human-robot interaction. Consequently, we generalized our study to industrial systems in which a human is in interaction with a robot (which can be a cobot) to accomplish a task in a given environment [7]. This includes systems where there is direct physical interaction between the human and the robot as well as when interaction is done via teleoperation.

We propose a methodology (section IV) that is being assessed on various workstations within Safran and Airbus Safran Launchers. The most advanced project aims mainly at improving work conditions on a tank cleaning workstation (see section II), where tanks are soiled with a pasty and sticky pyrotechnic substance. The application of our methodology on this workstation is presented in this article (through sections V and VI).

II. TANK CLEANING WORKSTATION ISSUE

Airbus Safran Launchers is specialized in the production of a pyrotechnic polymer. Tanks are soiled during the production process and they have to be cleaned to be reused. Tank's surface is cylindrical, top opened and with a hole on the center of the bottom surface. Tanks are 1 to 2 m high with a diameter of 1.5 to 3 m. Two main surfaces have to be cleaned in less than an hour: lateral and bottom. On the bottom surface residue is 1 to 10 cm thick, while on the lateral surface it is a few millimeters thick. This product being pyrotechnic, its cleaning is a specific process with a required level of safety. Moreover, this substance with high viscosity and stickiness is hard to remove.

Currently cleaning operations are done manually with four main stages: scrubbing tank's surface to remove most of the substance, scratching to unstick residues, evacuation through the tank's hole and a finishing stage for full cleanliness. For the first stage, most of the polymer has to be collected uncontaminated to be recycled using internal means. A plasticizer is used in the following stages to liquefy the polymer and facilitate cleaning. These operations are physically demanding for operators. Moreover they often have to clean several tanks in a row. There is a need to reduce physical load and enhance postures on this workstation.

Studies have been made for years within the company to improve the process of cleaning tanks. Numerous solutions have been tried, mainly solvent based, hydrodynamic and mechanical automation. Currently no satisfying solution has been found to improve operations and work conditions. Previously studied solution were not adopted because either too toxic, making the process more complex, or finally increasing operation time.

III. RELATED WORK

A. Cleaning robots and technologies

Harrington [8] listed three main industrial cleaning technologies: chemical (solvents, chemical solutions, scalding, streaming and ultrasonic), mechanical (brushes, pigging, drilling, scraping, abrasive blasting and ice crystals) and hydrodynamic (low to high pressure). Following cleaning systems use combination of these cleaning technologies.

When looking for tank cleaning, classical cleaning systems often use water. Rotating cleaning nozzles and static sprays balls are provided by companies such as Lechler GmbH for tank water jet cleaning. Unfortunately, they are reserved to clean closed tank, used in chemical, food, beverage, agriculture, pharmaceutical and other industries. Many companies such as Progressive Surface and C.E.B. Impianti provide industrial cleaning machines for opened tanks, but these systems are also water-based. Water-based cleaning is currently excluded in our application since it would contaminate the substance that has to be preserved to be recycled using internal means.

In the oil and gas industry, residues have to be cleaned from storage tanks. A oil tank sludge cleaning robot was created to remove 20 cm thick sludge from the bottom of a 5000 m^3 tank [9]. The robot is mobile with high-pressure water jet and a mechanical shovel. While this kind of system might be adapted for such massive tanks, it does not seem to be adapted to clean more little tanks as we have, with a dirty lateral surface, in less than an hour.

Other cleaning robots in the literature include robots for farms, houses [10], building, stores and pipe [11] cleaning. In particular, robots have been designed to clean floors, walls, stairs and windows [12]. But none of them are adapted to our application, because of tanks geometry and production constraints.

Other exotic solutions such as placing a veil on tank's surface before introducing raw materials were also considered. This would allow removing quickly all residues with the veil. Unfortunately, this is not compatible with previous production stages.

Although this benchmark guides us in the elaboration of a solution, none of them gave an answer to our specific problem. Indeed, we are looking for a solution to clean highly viscous and sticky pyrotechnic substance from open tanks in less than an hour. Using solutions to comparable problems would take too much time, contaminate the recyclable polymer, be too expensive or not be compatible with tank's geometry, the existing workstation and previous production stages.

B. Guiding collaborative robots introduction in the industry

Few initiatives are emerging to guide the introduction of collaborative robots on industrial workstations. In 2013, the Cetim released a guide to introduce collaborative robots in industries with a strong focus on health and safety standards [13]. Although their method consider projects globally (from the beginning, to setting-up and validation of a solution), it is centered on the technical solution and driven by risk analysis. Consequently, real work activity and human integration are less considered all along the project.

In 2016, a milestone for deployment of cobots in the industry was the publication of ISO/TS 15066 for collaborative robot system safety [2]. This ISO technical specification provides guidelines for the design and implementation of collaborative applications that reduces risks to people.

The assessment of the acceptability of human-robot collaboration was studied by Weistroffer & al. using virtual reality [14]. Maurice & al. introduced new methods and tools for the evaluation of ergonomics of human-robot collaboration, using virtual models of robots and humans [15]. This work strongly contributes to the biomechanical assessments of co-manipulation activities and to the optimal design of collaborative robots.

Yet many ergonomics aspects (such as development of activity, operators expertise, industrial variabilities, work determinants and organizations) are not integrated in these initiative. A global approach including these considerations would benefit to the successful introduction of interactive robot systems on industrial workstations, as demonstrated by ergonomists for design projects [5].

IV. PROPOSED METHODOLOGY

We introduce an approach to improve industrial workstations based on human-centered design [16] and on new possibilities given by collaborative robots. In this approach, inspired by ergonomics, a project team has to be formed to follow and participate in the design of the solution all along the project. This project team should be constituted at least with operators, their foreman, a project leader, a decision-maker, and ergonomics and robotics specialists. Depending on the project, other professions such as persons in charge of work instructions, maintenance officers, process experts and other specialists can be involved. To design new solutions adapted to operator's work, our interdisciplinary approach is based on the following steps:

a) Operators activity analysis: (observations, interviews, debriefings) for a better understanding of work situation, determinants, needs and variabilities, based on real work activity and not only work instructions [5]. When existing, similar situations should also be analysed. This analysis is driven by the ergonomist. The roboticist should participate to note technical constraints and assess the feasibility of automating operations and human functions.

b) Study of existing solutions: for similar situations (see section III-A). This step can be done concurrently with the activity analysis.The roboticist is particularly required for the research and the evaluation of robotic solutions. Previous attempts to improve the current workstation or similar situations in the company might have occurred, therefore the whole project team shall be involved to identify and assess past solutions.

c) Formalization in functional specifications: to facilitate exchanges and brainstorming of a solution with other experts. The ergonomist will guarantee the presence of functions resulting from operators activity analysis, for the design of a system that can handle the variabilities and that is adapted to every work situations and operators. The roboticist will include technical specifications related to operations and workspace constraints, for instance. Functional specifications have to be validated by the project team, to avoid missing important functions.

d) Development of theoretical solutions: first design assumptions, with the project team (applied in section V-A). The roboticist will bring his technical knowledge on the development of robotic parts and of human-robot interactions. The ergonomist will assess the solution's impact on human activity and the workstation. The rest of the project team will incorporate other constraints, for example on the process.

e) Iterative participative simulations: design, realization and evaluation of models of a theoretical solution with operators on more and more representative simulations. This iterative design is illustrated with Sections V-B, V-C and VI. Models of the solution are developed by the ergonomist and the roboticist with the project team to assess design assumptions. Models are the support to carry out simulations with operators. Their nature can vary from sketches, to cardboard mock-ups, computer simulations (including virtual reality), and prototypes. The choice of a model's nature is a tradeoff between its development time and its representativeness. Therefore it should be adapted to the design assumptions to be tested. The ergonomist prepares questionnaires to gather operators' evaluations and feelings during the simulations. During each simulation, the ergonomist observes operators' behavior and collect their verbal remarks, while the roboticist provides technical support. These participative simulations allow to develop operators' future activity [17] and the future process at the same time as designing the technical solution.

f) Industrialization: with operators in the loop for training and with the whole project team for system adjustments. This step ends when the system satisfies the needs of every person involved in the workstation.

g) Full production: with continuous evaluation and enhancement of the new system and operators' expertise.

V. FIRST DESIGN OF A SOLUTION THROUGH PARTICIPATIVE SIMULATIONS

A. Design of theoretical solutions

Following the presented methodology, the design of theoretical solutions is based on the activity analysis and on the study of similar situations. Our activity analysis highlighted that the various substance compositions to be cleaned on tanks vary in viscosity, tack (stickiness) and quantity. Also, operators have a strong expertise in the perception of product's reaction during cleaning to adapt

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their gestures and to use the proper tool. But operators' cleaning strategies are limited by the fact that they have to clean the tanks from the outside, for safety reasons in case of a pyrotechnic incident. From the inside and because of the tank's cylindrical geometry, more efficient cleaning strategies could be adopted. A properly designed system could benefit from such strategies. Besides, operators play a big part to ensure the cleaning quality. We tried to "objectify" the levels of cleaning using the "white cloth test" but operator's experience remains the only way to decide when remaining traces are residue to be cleaned or the plasticizer used to facilitate cleaning. Operators' experience and knowledge of the hazard of the substance (varying following the composition) also guaranties the safety of operations.

Therefore, operators have a strong expertise that has to be kept in perception and decision and action (gesture). Operations might be partly automated but operators remain an essential element of the solution. Moreover, there was a need of improving the workstation by taking operators away from the hazard during the operations on pyrotechnic residues. To answer these requirements and based on our knowledge of cleaning systems and interactive robot systems, we assumed that a telerobot with various levels of automation could be a solution based on three main assumptions:

(H1) Operator's expertise does not seem to be on his force control (at least not in real time), but more on understanding the substance's reaction to cleaning and using appropriate trajectories and strategies.

(H2) Robot system's autonomous functions could remove most of the substance quickly with a supervisory control [18] to let the operator adapt robot's behavior depending on operations success.

(H3) Its teleoperated mode could ensure the quality of operation giving more ability to the operator to express its expertise.

B. *Simulation of theoretical solutions*

Before starting a time consuming computer simulations, quick drawings of several theoretical solutions were done to discuss their match with the needs, with the project team. This step should not be underestimated. These simple simulations allow to quickly assess a great diversity of solutions and to advance rapidly in the basic design of a solution. The most credible solution was selected to be modelled and evaluated more precisely. The solution comprising a robotic part, this system was modelled on a robot simulator.

V-REP, a versatile robot simulation software [19], was used to simulate the designed robot system in the tank cleaning workstation. Its variety of control techniques, enables to easily control the simulation from external applications and control devices.

This simulation allowed advancing in the design of the future robot system and process. Robot topology, dimensions and mobility were chosen to guarantee accessibilities, reach of all tank surfaces and integration in the existing workplace. The various operating modes were considered for the design:

- normal: guarantee tank cleaning operation;
- transitory: facilitate robot's cleaning and maintenance;
- failure: anticipate robot removal in case of failure and allow manual cleaning operation without robot obstruction.

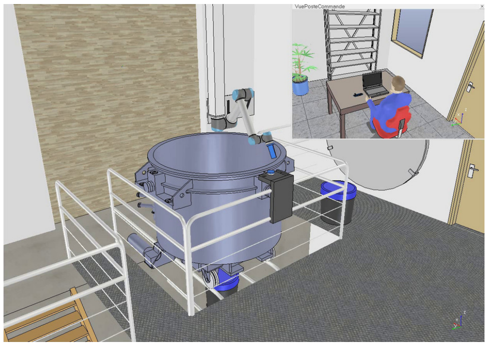

Fig. 1. Computer simulation of the theoretical robot system in the workstation and of a control room.

Operators activity analysis revealed that cleaning operations required a great variety of movements. Operators adapt the choice of tools and their trajectories depending on the substance composition, viscosity and tack. This need of flexibility guided the choice of a 6-axis articulated robot. For efficient robot dimensioning, it was put upside-down above the tank. Due to workstation geometry, the robot was put on linear axes to allow tank positioning below the robot, and to park the robot for maintenance, cleaning and in case of failure. Robot tool change was also taken into account to use tools adapted to each step of the cleaning process. The simulated theoretical solution is shown on Fig. 1.

A major milestone before going to the next simulation step was to show the simulated system to tank cleaning operators and the project team. It allowed to collect their impression on the theoretical solution, get their opinion of the simulated operations feasibility based on their expertise on real operations and start to imagine operators' future activity. For instance the feasibility of removing tank's lid, tools adaptation to clean every part of the tank and the position of the control room were discussed. Remarks were incorporated to improve our design.

C. *Simulation of human-robot interactions*

Once the robot system concept developed in the previous step was validated with the project team, we studied more precisely its interaction with operators. Following our assumptions (H2) and (H3), two control modes were to be studied: supervisory control and teleoperated control. For each control mode, basic system control (command, control devices, human-robot function allocation, interfaces) and data feedback (system parameters and states, camera views) were conceived. The previous simulation created on V-REP was improved to allow virtual robot teleoperation with control devices. The underlying architecture of this computer simulation is represented in Fig. 2.

Operators activity analysis revealed that scrubbing is the task that requires the greatest variety of movements and,

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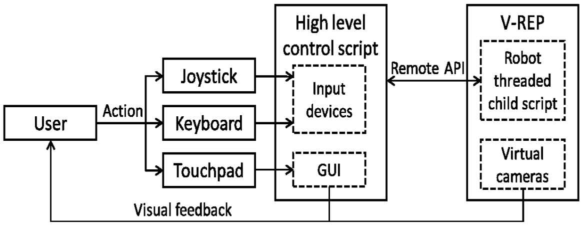

Fig. 2. Architecture of the interactive simulation: low level simulation control is performed within a V-REP threaded child script (Lua) and high level control is done inside a Python script using V-REP Remote API.

therefore, the highest degrees of freedom (DOF). Thus, we focused on this task for this first study of human-robot interactions. We assumed the other tasks require comparable or simpler interactions.

Tank's surfaces (bottom and lateral) can simply be projected on a plane, consequently two DOF are sufficient to control scraper's trajectories on the surface. A simple button was used to apply the tool on tank's surface. Scraper's orientation can also be constrained. One DOF was removed by constraining scraper's edge parallelism with tank's surface to simplify the task. The scrubbing angle[1] was also constrained during operations, since we assumed its continuous control would not add any value; it could be controlled separately if needed. Finally, the tool's direction on the surface was fixed for the lateral part, based on operators' experience. For the bottom part, we assumed that making the scraper point towards the center would simplify the task; discrete adjustments were possible if necessary. In this way, devices providing two DOF were sufficient for continuous control of operations. Two devices were implemented to control robot's tool trajectories: a joystick and a keyboard. We had following assumptions:

- Joystick (digital signal) is more flexible and intuitive;
- Keyboard (binary signals) is more constrained and gives more precision for some linear moves.

A simple Graphical User Interface (GUI) was created to provide high level control of the simulated operations to the user. The GUI allowed driving the simulated operations and stepping from supervisory control to joystick robot teleoperation and keyboard robot teleoperation.

During the activity analysis, operators' strong visual expertise was identified. Cameras are needed and have to be appropriately designed, so that operators can perform remote operations efficiently. The computer simulation enabled to quickly test visual feedback using V-REP virtual cameras. Indeed, virtual cameras' position and field of view can easily be changed. Three views were selected to be tested more thoroughly with operators: close task view, global task view and workstation view (Fig. 3). Close task view is done through a camera placed on the robot, near the end-effector. A camera placed on robot's first axis provides the global task view. The third camera is placed in a top corner of the workstation.

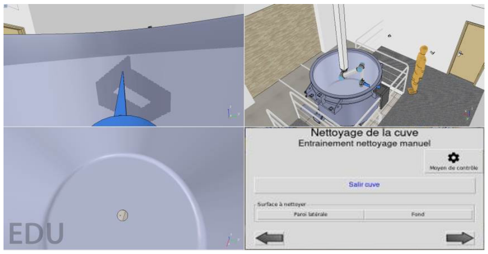

Fig. 3. Screen display for user tests on the interactive simulation: three virtual camera views are displayed at the same time as the GUI.

Fig. 4. Setup of user tests on the interactive simulation.

User tests were conducted to assess basic interactions and controls. The experimental setup for interactive simulation is shown in Fig. 4. The tests were conducted with 18 persons from Airbus Safran Launchers including 8 tank cleaning operators. The 10 other participant had an idea of the workstation process but were not familiar with it. Average age was 35 and nobody was familiar with robots. To avoid learning effects during teleoperated control, half of the population started with the joystick and the other half with the keyboard. Besides, a training step allowed getting familiar with the control device and cleaning process before starting the evaluated task. Anonymous questionnaires with multiple-choice and open questions were given to the users before and after each test. The test was conducted by two persons. Users' behavior, questions and remarks were written down, and teleoperated tasks were timed.

Many results were gathered from these tests to improve the interactive robot system design for the next simulation step. Some of the main results are summarized here. For teleoperated control, users preferred using the joystick, although their performance was similar to the keyboard on the simple task given. The joystick's flexibility also allowed to perform a greater variety of trajectories than the keyboard. Thus, operators can handle more process variabilities. Consequently the joystick was chosen for further evaluations under more realistic conditions. For both supervisory and teleoperated control, users were satisfied with virtual cameras vision for the lateral surface cleaning. They were unsatisfied with the close task view for the bottom surface cleaning because of insufficient field of view. Especially, near the hole, the robot was close to singularities and reached unwanted

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[1] Angle between the scraper's and tank's surface

configurations, disturbing the view. Despite that, according to operators, no more cameras were needed for this application. In particular two cameras seemed sufficient for the process control: one for global positioning and cleaning inspection and one for precise positioning and cleaning control. This was included in the design assumptions to be tested in future simulation steps. Finally, users highlighted the need to have an indicator to know when the robot was ready to be used.

VI. PROTOTYPE FOR REALISTIC PARTICIPATIVE SIMULATIONS

Computer simulations are limited in their representativeness, whether on the process and the substance mechanical/physical behavior, on robot's dynamics or on human-system interactions. A prototype is developed to test our design assumptions with operators under real conditions: such as robot inertia and workload, product viscosity and tack, and cleaning process sewage.

A. *Objectives*

The first objective of this prototype is to prove the technical feasibility of the robotic tank cleaning process and to give technical specifications for the future system: cleaning cycles, speeds, forces, tools, trajectories and robot control. The second objective is to design and evaluate human-system interactions for supervisory control and teleoperated control. Cameras positions, interfaces, control devices and appropriate level of automation of each task are studied for both control modes.

B. *Material*

Based on previous design steps, the prototype is composed of a 6-axis robot (Staubli TX90XL) ceiling mounted above a tank replica. This replica is made with the same stainless steel and surface roughness as original tanks and is composed of two parts (lateral and bottom). This prototype, set up on CEA Tech's TROPIC platform[2], is illustrated on Fig. 5.

For teleoperated control, a joystick was selected in the previous participative computer simulations. The prototype allows operators to test it under more realistic conditions. To evaluate our assumption (H1), a haptic device (Haption Virtuose 6D) was also implemented on the prototype. It enables to test the added value of giving force control to the operator. Moreover, it allows to assess the number of DOF necessary and sufficient for operators' cleaning activity. Two cameras are placed on the robot, as a result of the previous simulation step. The control station composed of the joystick, the master arm (haptic device) and camera views is displayed on Fig. 6.

For force control and for haptic teleoperation a ATI 6-axis force/torque sensor is mounted on robot's end. Robot cleaning tools were designed based on current operators' manual tools. Four tools were created for the four main stages of tank cleaning: scrubbing, scratching, evacuation and finishing (Fig. 7). For safety reasons, pyrotechnic product could not be brought to the platform. Instead a mechanically representative inert was used.

Fig. 5. Picture of the prototype on CEA Tech's TROPIC platform.

Fig. 6. Picture of the control station on CEA Tech's TROPIC platform. Joystick on the left. Camera views in the middle. Master arm Haption Virtuose 6D on the right.

Fig. 7. Pictures of the prototype tools for scrubbing, scratching, evacuation and finishing.

C. *Scrubbing process feasibility study*

Scrubbing experiments were conducted to determine the feasibility of automating this cleaning stage. A position/force control was used [20] with the force applied normally to the surface and position controlled in the surface plane. Various substance quantities and scrubbing speed, force and angle were tested to determine the influence of each parameter on cleaning quality and performance. At each iteration, one parameter's value was changed. These experiments highlighted that the scrubbing angle had little influence on cleaning quality. On the contrary, increasing the force applied to the surface improved the cleaning quality. Moreover, the influence of the scrubbing speed depends on the substance quantity and the normal force. Satisfying cleaning results were obtained for a nominal substance quantity (Fig. 8).

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[2] http://www.cea-tech.fr/cea-tech/Pages/en-regions/pfa-telerobotique-procedes-industriels.aspx

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Fig. 8. Successful robotic scrubbing experiment.

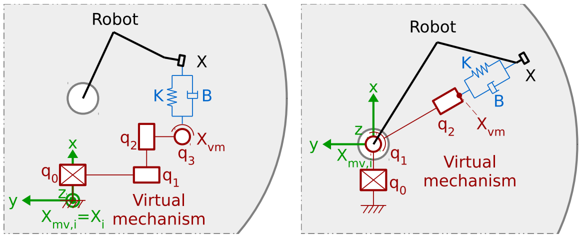

Fig. 9. Top view of virtual mechanisms displayed on a section of tank's bottom surface (4 DOF on the left, 3 DOF on the right).

D. Supervisory control design

For the future activity, we assume that a first cleaning step in supervisory control will improve global cycle time, by removing most of the residues efficiently. Previous experiments on scrubbing process feasibility gave encouraging results for this step. For best supervisory control, we want to optimize situational awareness [6]. Thus, just the required and most relevant feedbacks should be provided for each operation for an appropriate cognitive load. Cameras numbers, positions and fields of view are studied, as well as other data feedback (for instance, scrubbing forces, robot state, tools positions, current cleaning parameters and warnings). Human level of control on the system is also studied to be adapted to the task.

Simulations with operators and the project team are being conducted to determine best camera positioning for supervisory control. According to previous simulations and operators activity analysis, correct cameras feedback should provide awareness of robot/tool position in the tank, awareness of tank's global cleaning state and understanding the quality of current cleaning operation.

E. Teleoperated control design

The design of teleoperated control is highly important because this mode should enable the operator to use his expertise to ensure cleaning quality and to handle process variabilities. As stated previously, two control devices were selected to be tested: a joystick and a haptic device. The more DOF the control device provides, the more flexibility and variety of movements are given to the operators. However, at the same time, the task complexity increases.

As explained in section V-C, robot's motions were properly constrained to use a joystick with 2 DOF for continuous control. The tank being cylindrical, a custom control was implemented so that moving the joystick up and down would move the tool along a radius, and moving left and right would move the tool along a circular arc. Tool's speed is controlled along these directions. Tool's automatic force control on the surface was implemented using a virtual mechanism (VM) [21]. It could be enabled and disabled with joystick buttons.

On the other hand, the master arm (Haption Virtuose 6D) and the slave arm (Staubli TX90XL) are bilaterally coupled [21] to allow human's control of the force applied on the surface. Up to 6 DOF of the robot can be controlled with the haptic device. Virtual mechanisms are used to constrain motions and reduce the number of DOF. The robot end-effector is virtually coupled with a VM end-effector through a spring damper [20]:

$$F = K(X_{vm} - X) + B(V_{vm} - V)$$

with X_{vm} and X respectively the cartesian position of the VM and of the robot, V_{vm} and V the cartesian velocity of the VM and of the robot. B and K are the cartesian coupling gains between the robot and the VM, respectively the damping and stiffness gains. F is the wrench applied by the spring damper on the robot. The VM forward kinematics (L_{vm}) and its Jacobian (J_{vm}) define free motions, which are controlled in force, and constraints, which are controlled in position.

For our application, two VMs were implemented to guide tank's bottom surface cleaning. Implementation is now justified for the scrubbing task. It is identical for the other cleaning stages. 2 DOF are required to control tool's position on the surface and the substance pushing force. Another DOF allow to control the distance to the surface and the normal force. As with the joystick, a DOF was removed by constraining scraper's edge parallelism with the surface. As a result of automatic scrubbing experiments, one more DOF was removed to constrain the scrubbing angle that has little influence on cleaning quality. The last DOF corresponds to tool's direction on the surface. A 4 DOF VM was implemented to let this motion free and evaluate the benefits for operators. Another VM with 3 DOF was implemented to constrain this motion and evaluate if operators would perform the task more efficiently. The 4 DOF VM is composed of three prismatic joints (q0, q1, q2) and a revolute joint (q3) (see the left part of Fig. 9). Its reference position $X_{mv,i}$ is attached to a position corresponding to the robot end-effector's when created (X_i). The 3 DOF VM is composed of two prismatic joints (q0, q2) and a revolute joint (q1) (see the right part of Fig. 9). When created, its reference position $X_{mv,i}$ is attached to tank's center. In this way, the scraper is constrained to point towards the hole. Thus, the forward kinematics of the 4 DOF VM (L_{vm}^{4DOF}) and of the 3 DOF VM (L_{vm}^{3DOF}) are:

$$L_{vm}^{4DOF} = \begin{cases} Tx = q_2 \\ Ty = -q_1 \\ Tz = q_0 \\ Rx = 0 \\ Ry = 0 \\ Rz = q_3 \end{cases} \quad L_{vm}^{3DOF} = \begin{cases} Tx = q_2 \sin(q_1) \\ Ty = -q_2 \cos(q_1) \\ Tz = q_0 \\ Rx = 0 \\ Ry = 0 \\ Rz = q_1 \end{cases}$$

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Their Jacobian can easily be deduced and are not given. Similar VMs were implemented to guide tank's lateral surface cleaning. They are not described here.

As a result, various level of control on the task are provided to operators and are tested. The joystick gives the lowest one, and the haptic device constrained with a 4 DOF VM gives the highest one.

F. User tests and first results

User tests are being conducted on this prototype to evaluate human-system interactions for supervisory control and teleoperated control. In particular, joystick and haptic control for scrubbing and scratching operations are compared. The added value of virtual mechanisms is also studied. First tests with operators allow to give some tendencies and qualitative results:

- For haptic control, operators felt that 3 DOF VM was overly constrained. 4 DOF one is preferred.
- A third DOF on the joystick would be liked to control the tool's direction on the surface.
- Spatial awareness seemed more difficult with the haptic device than with the joystick.
- Without collision avoidance, focusing on the task was harder.
- The sound provided useful information for situational awareness.
- Lightning should be improved for better visualisation of residues.

VII. CONCLUSION

We presented an approach combining two disciplines (ergonomics and robotics) for the introduction of interactive robot systems on industrial workstation.

We illustrated the practical application of this approach on a pyrotechnic tank cleaning workstation. In this paper we focused on the design of an interactive robot system solution, based on simulations, from a technical point of view. But we also insisted on the major importance of involving operators and the project team at each step, in a human-centered design approach conducted by ergonomics and robotics specialists. This involvement is essential for several reasons:

- The introduction of an interactive robot system on an industrial workstation will have an impact on human work activity. It is the opportunity to design future work activity at the same time as the system.
- Operators provide their expert insight on how to perform the operations at best, to improve the design of the solution.
- Operators and the project team know workstation constraints and work determinants (whether technical, organizational, social). These inputs are fundamental to design a system adapted to every work situations and operators.

Finally, a prototype was designed to assess an innovative solution for tank cleaning operations. It proved technical feasibility for scrubbing operations and is promising to improve work conditions on the presented workstation. User tests on this prototype are being conducted to assess our design assumptions. First results and tendencies were given.

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