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A ROBOTIC CONCEPT FOR REMOTE INSPECTION AND MAINTENANCE ON OIL PLATFORMS

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ABSTRACT

This paper presents a novel concept for remote inspection and maintenance operations on next generation normally-unmanned offshore oil platforms. The concept is presented through the design of a robotic lab facility for automated and teleoperated inspection and maintenance operations by robot manipulators – ranging from simple inspection tasks to advanced maintenance operations. The lab facility is built around two co-operating robot manipulators equipped with sensors measuring temperature, vibrations, gas concentration and sound, and that automatically changes between tools to operate valves, exchange batteries in wireless sensors and to manipulate objects and the integrated process equipment. A graphical interface allows users to start automated inspection rounds where sensor data are collected, analyzed and compared to normal operating conditions, and alarms are generated if deviations are detected. Users may also plan new operations in a virtual environment before executing them, or remotely control the robots through a number of control interfaces. Live video feeds and stereoscopic vision are available to aid the operator during remote operations. A model-based collision avoidance system ensures that both automated operations and unplanned operations are verified before and during execution, and ensures safe operation of the robots. The paper presents results from the lab facility to illustrate the functionality of the remote inspection and maintenance concept, and demonstrate how remote operators may start automatic inspection and maintenance operations, plan new operations in a virtual environment, or directly control the remote facility onshore.

1 INTRODUCTION

Offshore oil and gas platforms are remote and isolated places, and pose a challenging environment for their human operators due to the unsheltered maritime environment, heavy weather and unfriendly, often explosive, toxic and corrosive atmosphere ([1]). Normally-unmanned automated topside platforms may be an alternative to subsea installations through increased accessibility for large maintenance operations. One of the major benefits of normally-unmanned automated platforms are less need for personnel, and thus costs related to sound insulation, footbridges and hand-rails and even catering may be significantly reduced both in the commissioning phase and during operation of the platform. In addition, statistically, subsea systems only manage to recover about 45 percent of the oil or gas in a reservoir, while a topside platform can take out almost 55 percent ([2, 3]).

This paper presents a novel concept for remote inspection and maintenance on automated topside platforms through a robotic lab facility setup. The lab facility demonstrates remote operation of offshore inspection and maintenance operations through a number of control options – automated inspection, virtual operation planning and direct control – and provides feedback and control of the remote offshore platform through a number of dedicated user interfaces.

Robotic solutions for offshore inspection and maintenance tasks have traditionally been through the use of remotely operated vehicles (ROVs) for subsea intervention and inspection, or in the use of autonomous underwater vehicles (AUVs) for geographic surveys and mapping of the seabed. Large maintenance robots have also been developed to repair subsea pipelines ([4]), and the focus of offshore robotics have traditionally been directed toward subsea operations due to their distant, dangerous and difficult-to-access locations. More recently, the idea of using mobile service robots in topside offshore applications have been introduced ([5]), and the main research focus has been on autonomous navigation ([1, 6]) in the unstructured environment today's existing installations represents.

Remote operation of robots in inspection and maintenance operations offshore is in many ways similar to controlling remote operations in space ([7]) or subsea ([8]), and also share many similarities with intervention tasks performed remotely in nuclear facilities ([9, 10]), demining applications ([11]) or in teleassisted surgery ([12]). However, remote inspection and maintenance operations on offshore oil platform often requires manipulation of heavier objects than in other teleoperation scenarios, and this may suggest the use of more traditional industrial robot manipulators that can provide the high degree of repeatability and the necessary lifting force required. Note though, that the industrial manipulator is traditionally a preprogrammed machine that allows very little online remote control when used in production lines and factories, and thus these robot manipulators must be extended both in terms of control modes and in terms of communication infrastructure to facilitate remote inspection and maintenance on offshore oil and gas platforms.

This paper presents the design and development of a robotic lab facility using standard industrial manipulators based on [13] for unmanned inspection and maintenance of offshore topside oil and gas platforms. The robotic lab setup facilitates autonomous inspection of the production processes, semi-autonomous maintenance operations such as valve operations and battery exchanges in wireless sensors, and offers control interfaces to remotely control inspection and maintenance operations either directly through joystick control, or through advanced planning in a dedicated virtual environment. The robotic solutions developed are aimed at replacing the eyes, ears and hands of field operators to improve Health, Safety and Environmental (HSE) issues as the operational staff will operate the installations from onshore, and thus minimizing the inherent risks of working offshore. Only during production shutdowns and scheduled large maintenance operations, a small service crew will be present within the process area. Robot-mounted sensors and actuators allow for sensor and actuator maintenance and repair outside the production area without shutting down production – not necessarily an option for automated production facilities without robot inspection and maintenance support.

This paper is organized as follows: A short background to the concept of normally-unmanned automated topside platforms is given in Section 2, while an overview of the robotic lab facility demonstrating the concept is given in Section 3. A description of the different control modes is given in Section 4, while some comments and conclusions are given in Section 5.

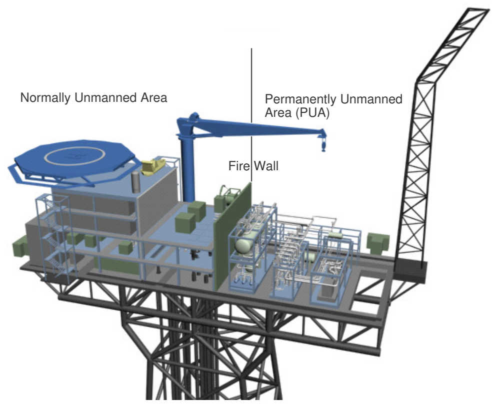

Figure 1. THE MESA VERDE PLATFORM CONCEPT.

2 BACKGROUND

The remote inspection and maintenance concept for offshore oil and gas platforms – the Mesa Verde platform concept – was developed by two Norwegian companies Aker Kvaerner and StatoilHydro. The platform concept is based on a principle of separating the work area accessible by human operators, and a closed permanently unmanned area (PUA) that is only serviced by robots as illustrated in Figure 1. The normally unmanned area allows a service- and maintenance crew to board the platform for large maintenance operations requiring replacement of larger sections of the process equipment using the onboard crane. This section incorporates living quarters for limited stays and is fitted with the necessary safety installations to ensure that HSE-issues for human workers are maintained. The normally unmanned section of the automated platform is separated from the production process by a permanent fire wall.

The permanently unmanned area is designed to only be serviced by robots, and incorporates all of the process equipment necessary for operation and production. The production process is not intended to be operated by robots, but will rather be built on concepts developed for subsea production platforms – but allowing easier access to the equipment for inspection and maintenance due to the topside location. Furthermore, due to the automated operation of the production process, costs and weight of foot bridges, hand-rails and other HSE-equipment such as sound proofing may be significantly reduced in the PUA. In particular, the concept of a PUA allows for new design concepts in the layout of a topside platform – where the layered structure with regular floors and levels may be abandoned for a more modularized and vertical layout of the production facility. Sensor and manipulation tools used by the robots for inspection and maintenance of the PUA can easily be moved from the PUA to the normally unmanned area for maintenance and repair by service personnel.

The normally-unmanned automated platform concept is designed on the premise that robots may replace humans for the

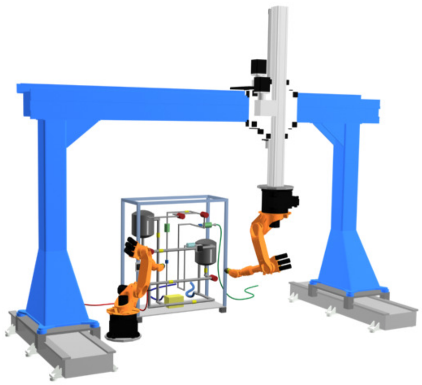

Figure 2. THE LAB FACILITY SETUP.

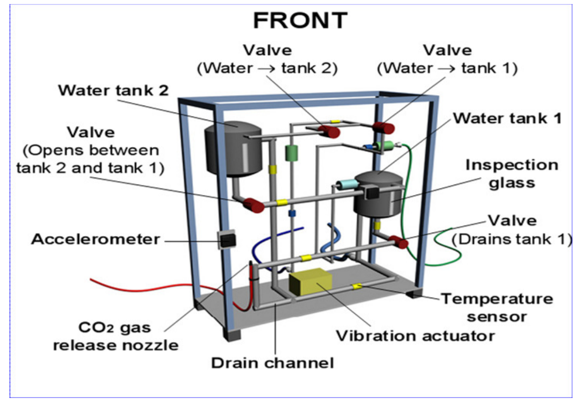

Figure 3. THE PROCESS EQUIPMENT.

most important scheduled operations ([1]); gauge readings, valve and lever position readings, and for monitoring gas level, leakage, acoustic anomalies and surface conditions. In addition, maintenance operations such as performing gas and fire detector tests, sampling the production process, pigging, cleaning and refilling are needed on a less frequent basis. The most frequent occasional operations are changing pressures, flow rates and starting and stopping equipment, and in case of emergencies identification and localization of the source, stopping the dangerous operations and evacuating/securing the are, and intervene to ensure safety by stopping a gas leakage or fighting fire.

The requirements for remote inspection and maintenance operations on offshore platforms may thus be formulated as to be able to replace the eyes, ears, nose and hands of an human operator to do regular inspection tasks, scheduled maintenance work and rapid interventions (repair) in the case of emergencies. To meet these requirements, a remotely operated inspection, maintenance and repair (IMR) robot must be able to communicate the necessary information to its onshore operator, perform the necessary maintenance operations on the platform equipment, and also ensure that all information is processed timely and that all operations are performed safely.

3 SYSTEM OVERVIEW

This section will present an overview of the robotic lab facility that demonstrates the concept of a normally-unmanned automated oil platform. The lab facility is designed to meet the requirements for remote inspection and maintenance as stated in Section 2, and consists of a process structure simulating the production process on the platform, and two robot manipulators performing inspection and maintenance tasks on the process structure using available sensors and tools, and relaying all relevant information to a human operator controlling the facility from a remote location.

3.1 Lab Facility

The lab facility is built around two standard six-degree-of-freedom (6DOF) robot manipulators (KUKA KR-16). Both robot manipulators are equipped with a pneumatic tool exchange system that allows for easy access to a range of sensors and tools placed in a number of tool racks in the lab facility. One of the robot manipulators is mounted on a gantry system providing an extra three-degrees-of-freedom in order to increase the flexibility and range of the robot motion as depicted in Figure 2. The gantry mounted robot is the main inspection and maintenance robot in the facility, and may perform automated inspection rounds and scheduled maintenance on all parts of the process structure due flexibility and range. The floor mounted robot is fixed in the facility, and its primary task is to assist the gantry robot with additional tools or views during the operations. Both robots may be individually controlled by a remote operator, or synchronized in automated operations to allow a cooperation in the execution of tasks.

The process structure used to simulate the offshore production process is illustrated in Figure 3, and consists of two water tanks, four valves to control the water flow, and is fitted with accelerometers and a range of temperature and pressure sensors. The process equipment is also equipped with a CO_2 release nozzle to simulate gas leakage, and a vibration actuator that produces vibration in the process equipment with a specified amplitude and frequency. The temperature of the water flow may be controlled over a wide temperature range, and the water may also be mixed with air to simulate air pockets. A more detailed description of the lab facility may be found in [14] (see also [15, 16]).

3.2 User Interfaces

The lab facility is fitted with range of user interfaces providing information on the state of the facility through cameras and sensors, and also to control the robots inspection and main-

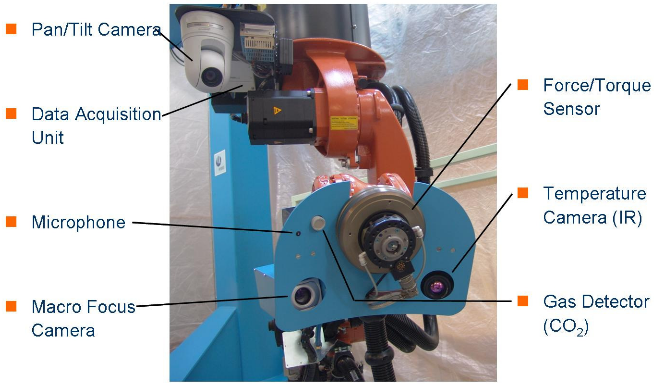

Figure 4. THE GANTRY ROBOT SENSOR SYSTEMS.

Figure 5. SENSOR AND MANIPULATION TOOLS.

tenance operations through haptic control devices and joysticks. The devices are chosen to act as remote eyes, ears, nose and hands of the human operator to provide the sufficient and necessary information on the state of the process to the remote operator.

3.2.1 Cameras The lab facility is equipped with a number of cameras that provide instant visual feedback to the remote operator during operation. An overview camera is mounted on the right leg of the gantry crane in Figure 2 to provide an unobstructed view of the crane robot motion during inspection and maintenance operations on the process structure. An additional camera is mounted on the base of the gantry robot – where it is attached to the gantry crane in Figure 4 – and provides a second, and closer, view of the operation of the gantry robot. Both these cameras are mounted on pan and tilt platforms, and thus may automatically track the motion of the gantry robot in the facility. They may also be directly controlled by the remote operator to focus on other objects. A third camera is mounted in the sensor rig on the tip of the crane robot (on the left in Figure 4) to provide a close up view of the process structure during the robot operations. The sensor rig also holds an infrared camera for measuring temperature.

The floor mounted robot does not hold a permanent camera, but may be fitted with a stereoscopic camera tool as seen in Figure 5 providing three-dimensional feedback to the remote operator. The 3D camera tool is fitted with two high-resolution cameras transmitting live images at a high bandwidth rate, and the alternating images are displayed on a screen that is synchronized with specialized LCD-shutter glasses that closes one eye at the time. At high display rates, this provides a 3D effect that visualized depth information to the remote operator otherwise lost in the 2D images from standard cameras. The 3D display is also overlaid with information illustrating the distance to the nearest object for increased depth-perception, and thus provides an augmented reality environment to the remote operator.

3.2.2 Sensors and Tools The gantry robot is fitted with a range of permanent sensor providing information to the remote operator on the state of the production process, and may also be equipped with a range of different specialized sensors through the tool exchange system on the robot. While sensors in the process equipment provide internal state information of the process, such sensor may fail or become uncalibrated over a long operation time. The goal of the external sensors is to provide an external validation of the state information for the process equipment, and thus act as the remote human senses offshore. The gantry robot is permanently equipped with a microphone to measure sound, and a gas detector that measures CO_2 concentration. In addition, the both robots are equipped with force/torque sensors that measures the contact forces between the robot and any interaction with the environment through tools and actuators.

The robots may also chose between a set of sensor tools through the tool exchange system as illustrated in Figure 5. A laser vibrometer measures vibrations in structures without connecting physically to the process equipment, while a contact based vibration sensor combined with a single point temperature sensor requires interaction with the process equipment for more reliable vibration measurements.

3.2.3 Manipulation Tools A number of manipulation tools is available to the robot for interaction with the process equipment. A valve operation tool has been custom made to reduce the contact forces on the process equipment when opening and closing valves, and is an important tool for shutting down operation in case of any failure in operation of automatic valves. A gripper is used as a versatile tool for picking up lost objects, manipulating general fixtures and also to aid in the exchange of

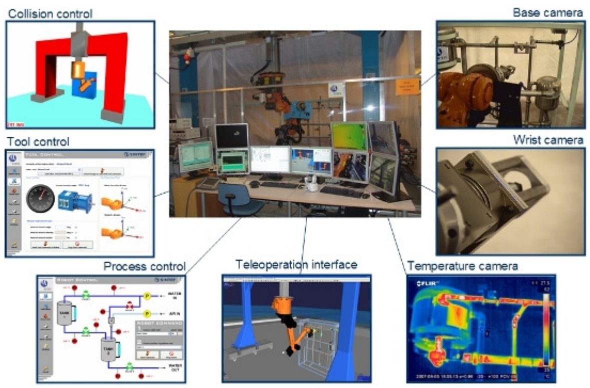

Figure 6. CONTROL ROOM AND USER INTERFACES.

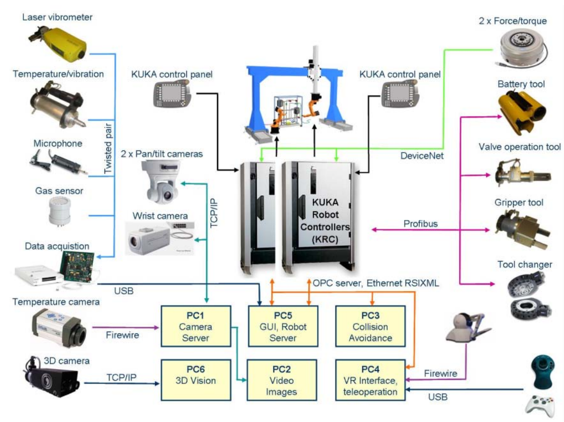

Figure 7. COMPONENTS AND COMMUNICATION INTERFACES.

batteries on wireless sensors using a specialized custom tool. The gantry robot unscrews and removes the lid of a wireless sensors using the custom battery exchange tool, while the floor mounted robot replaces the battery of the sensor using the gripper. The gantry robot then screws the battery lid back on the wireless sensor.

3.2.4 Control Devices

The remote operation of inspection and maintenance tasks on an offshore platform requires not only that sufficient information is available to the remote operator, but also that the necessary interaction with the process equipment; such as closing a valve, exchanging batteries in wireless sensors, picking up or manipulating general objects, may be performed accurately from a remote location. The control room includes four different interfaces for controlling the remote operations; a process control interface, a haptic six-degrees-of-freedom (6DOF) device, a 6DOF computer mouse and a gaming joystick. The main user interface is a process control interface graphically representing the production process, and allowing the user to issue control commands to inspect pre-defined measuring points on the process structure using any of the available sensors, or to open and close any valves to change the flow of water through the structure. In order to account for unforeseen tasks, it is also possible to plan and execute new tasks using the other user control interfaces. To this end, the motion of the robots can be controlled either by planning their motion on a 3D model of the facility or by direct motion control of the robots. Both these two scenarios are described further in Section 4.2.1. In order to control and plan such motion of the robots, the remote operator may choose between a haptic pen device controlling the robot arm which is capable of providing force feedback during the operation, or a 6DOF computer mouse commonly used to navigate in 3D applications. Both these devices control the robot manipulator as *arm* movements; the robot performs the same (or a subset) motion as the arm and wrist motion of the remote operator. For some, the first-person control view found in computer games is more intuitive, and a Xbox-joystick controller can be chosen to allow the remote operator to control the robots as if the robot manipulator is the body of the operator moving forward in the three-dimensional space. The choice of control device is also operation specific; for larger and longer motions the joystick may provide an intuitive relative displacement in space, while for more accurate motions the 6DOF mouse or the haptic device may provide better accuracy of manipulation.

4 CONTROL MODES

The remote inspection and maintenance operations of the automated offshore lab facility may be controlled in three different modes. 1) An automated process control modus allows the user to issue high-level control commands to the inspection and maintenance system without regard to the fact that the operations are being performed by robot manipulators. 2) A virtual teleoperation interface allows the remote operator to plan new inspection and maintenance operations in a virtual environment before executing them on the real system, while 3) a direct control option allows the remote operator to directly control the robot manipulators using the control devices as described in Section 3.2.4. Note that the remote operation control system is designed to be implemented in an onshore control room, while the robot manipulators and production process equipment illustrates the remote offshore equipment of the PUA of next generation oil and gas platforms. The control room and the robotic lab facility is linked through general communication interfaces as described in Figure 7 that allows remote operation of the lab facility from anywhere in the world; and operation of the lab facility placed in Trondheim, Norway, has been demonstrated from Amsterdam, the Netherlands, during the Intelligent Energy 2008 conference.

4.1 Automated Inspection and Maintenance

The automated inspection modus is the normal form of operation for the remote inspection and maintenance robotic facility. The operator controls the inspection and maintenance operations by choosing from predefined sets of operations in the process control interface shown in Figure 6.

4.1.1 Inspection Rounds with Trend Analysis

The remote operator may choose between a set of predefined inspection rounds that performs a range of measurements for a selection of inspection points on the production plant. The different automated inspection scenarios may include a complete inspection measuring gas, sound, temperature and vibration of some inspection points on the process structure, or target a subset of measurements for all inspection points on the structure. The remote user does not interact with the inspection and maintenance robots directly, but simply chooses the desired operations from the process control interface. The appropriate measuring device is automatically retrieved from the tool exchange system. Looped inspection and maintenance rounds are also possible; where the inspection rounds run without remote user interaction indefinitely on the production plant while recording and time stamping measurement data.

In addition to targeted inspection operations initiated by the user, the automated inspection and maintenance operations allow for a trend analysis of the data collected from each inspection point over time. For indefinite inspection rounds of all inspection points, or for each time the operator targets a specific inspection point, the measurement data is stored, analyzed and compared to historic data for that particular inspection point. All the historic data for the production plant comprises a set of "normal" operating conditions linked to the particular operation of the production plant. Thus, new measurements from inspection points may be instantly analyzed and compared with the normal operating set, and any detection of deviation from the normal operating conditions may generate an alarm. The trend analysis is linked both in time and space; measurements must show a significant change of state over time for the trend to raise an alarm, and measuring points are logically linked to the production flow to determine if measurements are wild-points for the sensor or indicative of a change in the production flow. Note that, as described in Section 3 and in Figure 3, the lab facility setup allows experiments to be conducted through perturbation of the water flow, temperature, water-to-air mix or by introducing vibration or CO_2 gas emissions. The trend analysis monitor runs continuously in the background while operating the facility, and may generate alarms to the remote operator when a deviation from the normal operating conditions is detected. The remote operator may then choose from a number of preplanned operations, e.g. closing valves, to return the state of the production plant to the desired operating conditions.

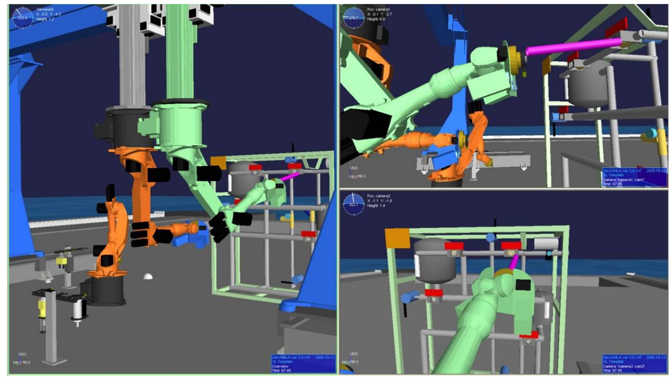

Figure 8. SIMULATION AND VISUALIZATION INTERFACE.

4.1.2 Planned Maintenance

The remote user may choose between a set of preplanned operations to interact with the production plant either for planned maintenance operations or for emergency repair operations. The remote operator may select an object in the production plant, and choose between a series of operations linked to that object. A valve operation may be executed from the process control interface, and the robot will automatically retrieve the appropriate valve operation tool from the tool exchange system, and proceed to open/close the desired valve without any further human interaction. The operator may also perform planned maintenance on parts of the production plant through exchanging of batteries in the wireless sensors – a challenging robotic operation due to fact that the wireless sensor is designed for human operation with two hands. A special tool has been designed to unscrew and reattach the battery lid of the sensor with one robot (see Figure 5), while the other robot replaces the battery. The principles of this operation may be extended to a wide range of planned maintenance operations requiring the robots to replace parts of the production plants due to failure. Note that the remote operator does not have to consider that the maintenance is performed by a robot, but simply chooses the desired operation from the process control interface.

4.2 Virtual Planning

Inspection rounds are the choice of operation for preplanned remote inspection and maintenance operations. However, the remote operator must also be able to plan new operations without being physically present on the remote facility to cope with changes in the production plant, unscheduled events, loose or lost objects, or emerging failures in the structures for inspection points that are not predefined during installation of the system.

4.2.1 Way-Point Planning

An onshore operator may plan new operations for the robot manipulators on a 3D model of the platform facility through a virtual interface as seen in Figure 8. The simulation and visualization interface ([17]) shows the two robot manipulators and the process production plant on the remote offshore facility, and allows the operator to control the motion of the two manipulators in the virtual environment using the 6DOF mouse or the haptic device as described in Section 3.2.4. The planned motion of the "virtual" manipulators may be stored through user defined way-points that completely describe the configuration of the manipulators at each point. The motion between the way points is calculated automatically through a path-planning system, and the resulting motion may be played back to the operator for verification before being executed on the actual remote facility. The resulting motion is also checked for collisions with an integrated collision avoidance system described in the following section.

4.2.2 Collision Avoidance System While pre-planned inspection and maintenance operations may be verified during installation, new operations planned by the onshore operator in the virtual environment must be checked for collisions before execution on the remote offshore facility. A collision avoidance system, CRASH, has been designed to check all new motions of the robots against the complete model of the facility for collisions, and the program reports the shortest distance from the robots to any of the surrounding objects, or if the planned motion will generate a collision, back to the control system. Thus, when executing a new operation planned in the virtual environment, the CRASH system will check the motion of the robot manipulator for collisions with the fixed structures and robots in the facility before allowing the user to execute the new motion path safely on the physical robot system at the remote facility.

4.3 Direct Teleoperation

In addition to the option of planning new operations through way-points in a virtual environment, the remote operator may also control the robot manipulators directly through the 6DOF mouse and the joystick described in Section 3.2.4. This may be the choice of operation when manipulating loose or unidentified objects in the production plant that are not in the 3D model of the remote facility employed in the virtual environment. The option of directly controlling the robot manipulators imposes strict limitations on the velocity of the manipulators when moving around in the remote facility, and the collision avoidance system CRASH constantly monitors the motion of the robots to check the shortest distance between the robots and the fixed structures in the facility to avoid any collisions. When this distance drops below a given threshold, direct control of the robots is automatically prohibited and the operator must pre-plan the robots' motion in the virtual environment in order to move the robots safely away from their surroundings.

5 COMMENTS AND CONCLUSIONS

This paper has presented a robotic lab facility for inspection and maintenance operations on future normally-unmanned topside offshore oil and gas platforms. The lab facility simulates the offshore production platform using a mock-up production process plant where parameters such as water flow/temperature, vibrations and gas concentrations may be varied based on user choices. The process module is inspected automatically using two robot manipulators equipped with sensors and tools that may be controlled through a process control interface, or through dedicated control devices. A remote operator in a simulated onshore control room may choose from a set of predefined inspection and maintenance operations that are executed without direct operator interaction with the actual robot manipulators, but may also take control of the robot manipulators in a virtual environment based on a model of the facility, or directly through dedicated control devices. All new robot operations are checked for collisions through a collision avoidance system that ensures that the robot motions are safe to execute on the remote facility.

Note that the planning of new operations in the virtual interface requires that the model of the remote facility is accurate, and this is also a requirement for verifying the integrity of new motions paths in the collision avoidance system. An accurate model may be difficult to attain after the initial installation of the remote facility, or may become obsolete due to tear and wear of the equipment or new installation done by human service personnel. To meet these requirements, work is now ongoing on using the robots to accurately map the production structure using scanning sensors, and updating the model accordingly. This will also allow for more accurate positioning for large structures using local feature detection to relatively position the robot manipulators to the process structure.

Automated inspection rounds with trend analysis together with the various cameras and other sensor readings presented to a remote operator will aid in the challenging tasks regarding asset integrity issues. Unforeseen problems are often detected during informal inspection rounds on manned oil platforms. Therefore, one of the challenges of remote operation is to convey the necessary amount of information to the remote operator in order for him/her to detect the same discrepancies as he/she would have found by being present on the platform. Moreover, automated inspection rounds with trend analysis will prove important for detecting deviations. The automated inspection and trend analysis algorithms will constantly develop and improve as more research is put into this field. In addition, these systems will constantly improve by learning from experience once the first normally-unmanned platform is put into operation.

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