Real-world demonstration of sensor-based robotic automation in oil & gas facilities

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***Abstract*— The focus of this paper is our recent real-world demonstration using an industrial robot certified for running in explosive atmospheres (ATEX). The demonstration is run amidst live and running hydrocarbon processes and involves autonomous valve manipulation and thermal inspection operations. The valve manipulation operation involves sensor-based movements which implies that the robot trajectories have not been programmed *a priori* (off-line). In particular, an approach will be presented to sense and avoid over-tightening/loosening of the valve. To the best of our knowledge, this prototype is the first system that performs sensor-based close-contact operations in a real operational environment.**

I. Introduction

In recent years, it has been necessary to seek oil and gas in increasingly remote and hostile environments, as most of the easily-accessible fields are nearing, or already depleted. The exploration of the Stockman- and Kashagan fields serve as a testimony of this. These new fields can often pose greater risk to safety and the environment, and thus there is increased emphasis on the importance of safe operation, particularly with recent events such as the Deep Horizon oil spill in the Gulf of Mexico.

Novel technical solutions, working practices and business models have to be employed to enable the safe operation of these remote locations. This explains the industry's emphasis on utilizing robotics technology as an enabler to perform various inspection, operation and maintenance operations in next-generation normally-unmanned production facilities. It is notable that existing decentralized automation equipment is used today for remote operation of modern petrochemical facilities, however, our studies conducted in collaboration with oil and gas companies show that complete automation of oil & gas facilities requires an automation system capable of around 1000 additional operations that are performed today by on-site staff. These operations include valve manipulation, sample-taking, scraper handling, daily inspection rounds and maintenance work, *e.g.*, instrument replacement or cleaning.

The main drivers for using automation in general and robotics technology in particular are to improve health, safety and environment (HSE), as well as production and cost efficiency. By relocating humans from remote, harsh and unpredictable environments to more conveniently located control rooms, dramatic improvements in HSE and business value are expected. This allows lifetime extension of existing facilities (upon renovation) while making development of new marginal fields affordable.

There are however some major challenges along the way that have to be addressed (see [1]). Our strategy for meeting these challenges is based on a step-by-step approach involving development and validation of the technology in increasingly demanding settings.

This starts with proof-of-concept demonstrations in our indoor test facility located in Oslo, Norway [1], [2]. Taking this one step further, robots and applications are tested and validated in a co-located outdoor test facility. This is normally an intermediate step before bringing demonstrators onto real oil and gas facilities [2]. Operating reliably and safely in such conditions raises awareness and confidence in the technology and in partners' organizations. The strict operational requirements of our prototypes detailed in later sections are often absent in academic or industrial research, as many prototypes only run in a lab environment for a short period of time. In this paper we hope to identify some of the challenges faced in creating novel robotic solutions for applications with an extremely high focus on safety and robustness.

II. Related Work

Developing a reliable and intelligent robotic system which enables the operation of normally unmanned oil & gas facilities requires solving a number of challenging sub-problems. Aspects that need particular attention include operator interface [3], control room visualization [4], high-level robot allocation and task scheduling [5], [6], safe human-robot interaction and collision handling [7]–[9], motion planning [9], [10], safety and reliability of the SCADA control networks [11], [12], camera viewpoint planning and 3D mapping [13], [14] and telerobotics [15].

Nevertheless, one must bear in mind that even if all these sub-problems were solved in a satisfactory manner, system integration would still remain a grand challenge. Work in this direction includes robotic prototypes for industrial maintenance and repair applications [16]. Other research efforts on building functional prototypes of outdoor robots include domains such as agricultural robots [17], [18], animal-farming [19], [20], mining [21] and power plants [22]–[24]. However, as stated previously and witnessed in [25], confronted with the extremely high demands on robustness and stability of the industry (*e.g.* stringent requirements on up-time, MTBF and the 20+ years facility lifecycle expectancy), most of these R&D prototypes fall short. As an illustrative example, although the inspection and

This work was supported by Statoil and Norwegian Research Council (NFR) through the Jupiter Robotics project.

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manipulation objectives described in [24] are reminiscent of those described in this paper, the 90% success-rate is clearly below the acceptance rate for real-world deployment in oil & gas facilities amidst live hydrocarbon pipes.

Two other research groups working with robotic technology specialized to the needs of the oil & gas industry are Fraunhofer IPA and SINTEF ICT. Fraunhofer IPA has developed a first hardware prototype of a mobile robot called MIMROex. The main research focus has however been on autonomous navigation capabilities [26]. SINTEF ICT has developed and tested various system components in their indoor lab facility [27] but preparing the system for harsh environmental conditions has however not been a part of SINTEF's agenda so far.

III. Demonstration Description

Both the autonomous valve manipulation and thermal inspection operations described in this paper have been selected and developed in close collaboration with the current operators of the site in which the demonstrations are run. Currently, valve manipulation occurs in conjunction with flow assurance tests that are run in this part of the process. With the objective of being able to run these tests entirely from remotely located control rooms, the site operators requested fully autonomous valve manipulation functionality. The thermal inspection operation was recognized for its ability to provide complementary temperature measurements of parts of the process used in the flow assurance calculations.

This section will be devoted to provide details on both the autonomous valve manipulation and thermal inspection operations. This is done in Section III-A and III-B respectively.

A. Valve Manipulation

Before embarking, it should be noted that although actuated valves are frequently used in the industry, the request for developing a robotic valve manipulation application from the operators was nevertheless granted. This is because robotic valve manipulation was found to contain a number of challenging sub-problems of more generic nature that need to be addressed. These include but are not limited to the design of the human-machine interface (HMI) and online generation of safe movements while performing high-accuracy, close-contact operations.

The valve manipulation operation is to be initialized by the remote operator via the HMI where he/she can order to open or close the valve by a chosen number of degrees. The system is then expected to flawlessly perform the requested operation while keeping the remote operator aware of the progress status. The technical requirement specification is as follows. The accuracy of the maneuver must be within $\pm 1^\circ$ and naturally respect the mechanical limitations of the valve. Eliminating the risk of over-tightening/loosening the valve, although such a maneuver has been requested by the operator, is probably the most obvious and potentially dangerous safety aspect associated with the valve manipulation operation. The solution suggested in Section IV-B heavily stresses this issue and involves both torque overload detection as well as empirical safety tests (See Section V-A and V-B). Also, since people may independently manipulate the valve manually, the exact orientation of the valve handle in the xy-plane cannot be assumed to be known in advance (*cf.* Figure 1). Hence, a robust way of sensing this must take place. Also, since the z-coordinate of the valve position changes on this type of needle valve as it is turned, that entity must be detected as well. To our advantage however, is the relatively slow settling time of the hydrocarbon process which implies that completion of the valve manipulation operation does not have to occur faster than approximately 3 minutes.

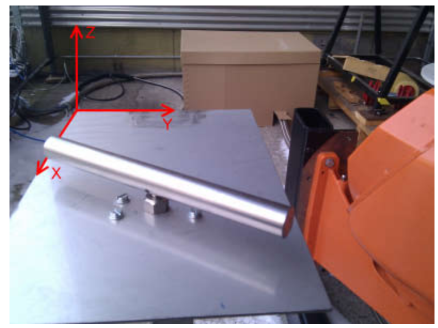


Fig. 1. Although the position of the center of the valve is known in the xy-plane, the exact rotation of the valve handle in the xy-plane and the vertical position of the valve (z-coordinate) are not known *a priori* and hence must be accurately and robustly detected. The accuracy requirements on the operation is set to $\pm 1^\circ$. The provided solution is considered to be successful as long as it is accurate enough, perfectly safe, flawlessly performed and takes a couple of minutes to complete.

B. Thermal Inspection

Obtaining accurate and reliable thermal images is a quite complex task whose quality strongly depends on the surfaces to be measured. The accuracy and repeatability of the robotic solution is then of great advantage as it can be used to reduce the influence of reflection. The thermal inspection operation is expected to acquire temperature images from predefined parts of the process. The expected outcome is storage of the thermal images in a historical repository for future analysis. As previously mentioned, this data serves as complementary temperature measurements for the flow assurance calculations on parts of the process. This is a non-contact operation and is mainly executed automatically according to a predefined schedule at various predefined locations. Additional measurements should however be possible to initialize by the remote operator at any time instance.

IV. Solution Description

This section provides details on the proposed solution that successfully performs the two demonstrations described in Section III. Although the two operations have different requirements and way of realization, they also share some features, most prominently the HMI and the used tool.

Next, the HMI and the tool design will be examined while other aspects of the solution which are special to the valve manipulation and thermal inspection operations are treated in Section IV-B and IV-C respectively.

A. Human Machine Interface (HMI) and Tool Design

1) HMI: One cohesive interface is used for initiating, controlling and supervising operations. The central element of the interface is the 3D visualization of the process. Referring to the view in Figure 2, the robot's activity can be observed, and various objects within the view are interactive. Images from cameras are integrated and shown in correct perspective, thus augmenting the 3D view with live video from the thermal camera or other cameras. "Points of interest" are listed on the left side of the screen and serve as interactional shortcuts for frequent objects. A "faceplate" can be shown for a given object, which lists various metadata and a list of possible operations for the object. A modular, flexible system architecture means that a single lightweight client application can control all of the system's operations anywhere there is a secure network link established.

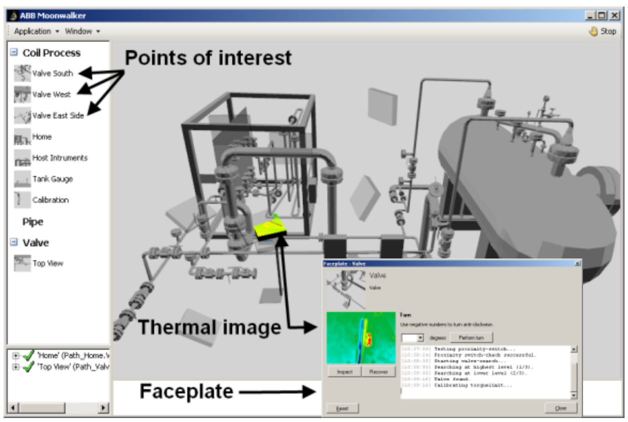


Fig. 2. Screen shot from the HMI.

2) Tool design: The robot tool holding the ATEX certified thermal camera, sensors and the valve manipulation device (Figure 3) is based on a bar of stainless steel that interfaces the robot arm. This bar has multiple functions, acting as both mounting plate for the thermal camera, sensors and foundation for the valve manipulation device. It also has openings where the tool's power and signal cables pass through.

The circular valve manipulation device consists of two spring-suspended circular rods with different diameters and a ATEX certified proximity sensor. The inductive proximity switch is mounted at the end of the valve manipulation device to enable the robot to detect the valve handle.

B. Valve Manipulation

Central to flawless completion of the valve manipulation operation is the valve manipulation device integrated into the tool as described in Section IV-A.2. As depicted in Figure 1 and 3, the selected valve is modified with an enlarged handle in order to ease robotic manipulation. The proximity sensor mounted at the top of the tool is utilized to detect the orientation of the valve handle in the xy-plane, as well as its vertical z-coordinate. This type of inductive proximity switch is widely used within the industry and provide an extremely

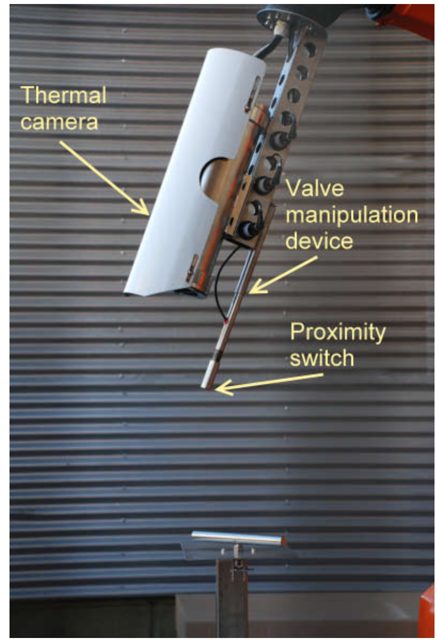


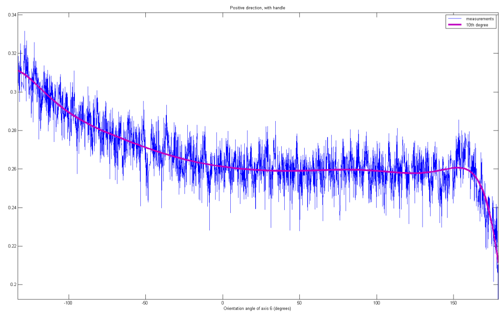
Fig. 3. The tool comprising thermal camera, sensors and valve manipulation device.

robust way of detecting presence of metal. Nonetheless, the robot will always perform a functionality test on the proximity test in the beginning of each operation by moving it close to its own metallic body and checking the sensor output. Although this detection procedure is extremely reliable and has been flawlessly performed at all instances, the spring suspension is introduced as an extra layer of safety in order to limit the risk of the robot damaging the valve in the unlikely case of erroneous detection.

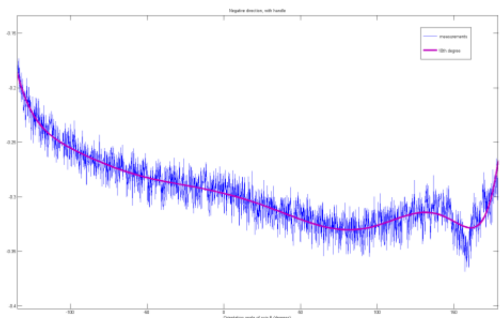
The maximum torque level tests performed and described in Section V-A provide an upper bound on the absolute value of the applied torque. However, empirical tests reveal that the torque level required to rotate the tool around the z-axis (by solely using axis six on the robot) is not constant. In addition to the rotation angle, it mainly depends on the outdoor temperature which naturally affects the internal dynamics of robot arm.

To address this and be able to detect over-tightening/loosening of the valve in an early stage, an accurate model for the inherent level of torque in the robot arm as a function of the orientation angle was developed. For our practical purposes, a 10^{th} degree polynomial was found to be accurate enough. The outcome of this can be seen in Figure 4.

The polynomial model is then used in order to compensate for the dependence of the torque level on the orientation angle. Let $\Delta \in \mathbb{R}^+$ denote a constant threshold above which the valve is being overtightened/overloosened. Let further $\tau(\theta)$ denote the torque level measured from the inbuilt sensors. From the figures, it can be concluded that a simple stopping criteria such as $|\tau(\theta)| > \Delta$ is not suitable to use in this setting since the right hand side clearly do not depend on the orientation angle, θ. In contrary, letting $M(\theta)$ denote the



(a) Positive direction.



(b) Negative direction.

Fig. 4. The 10th deg. polynomial fit, $M(\theta)$, vs. the orientation angle, θ.

polynomial model stemming from the measurement series, $\tau_M(\theta)$, one can readily use

$$|\tau(\theta)| > |M(\theta)| + \Delta_1$$

as criteria for torque overload detection. Here, $\Delta_1 \in \mathbb{R}^+$ denotes a constant proportional to the variance of $\tau_M(\theta)$.

Addressing hardware specific differences originating among others from outdoor temperature changes, relies upon a calibration round that is run on-line just before the start of the turning maneuver. This calibration occurs in a set of connected orientation angles $\Theta \subset \mathbb{R}$. The adopted stopping criteria is then modified according to

$$|\tau(\theta)| > |M(\theta)| + \Delta_1 - \Delta_2 + \max_{\theta \in \Theta} |\tau_C(\theta)|. \quad (1)$$

where the constant $\Delta_2 = \max_{\theta \in \Theta} |\tau_M(\theta)|$ is computed off-line and $\tau_C(\theta)$ denotes the measurement made during the calibration procedure.

C. Thermal Inspection

Acquiring and storing thermal images from the on-board thermal camera is a non-contact operation. To keep this feature intact, the designed HMI only allows the operator to move the robot to *predefined* viewpoints at a safe distance from the process equipment. It further comprise no work-around to move the robot to different positions or alternative orientations. As a feedback to the operator, the thermal image is presented within the operator interface and stored in the historical repository for future analysis.

This operation is mainly executed in automatic mode according to a predefined schedule. This automatic cycle is run 24/7 at seven different sample points. The operator is however able to manually start additional inspection rounds from the control room at any time. Figure 5 shows one of the obtained thermal images.

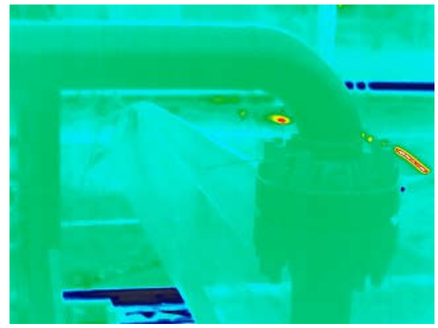


Fig. 5. Thermal pictures of the pipe.

V. Safety procedures and tests

This section briefly presents some of the safety related issues that had to be investigated and addressed before permission to perform sensor-based robot manipulation was granted on an operational oil & gas site. The main objective is to illustrate and emphasize the stringent requirements regarding safety and robustness which may be lacking in academic projects.

To begin with, our proposed robotic solution had to go through extensive risk assessment studies including both the Hazard and Operability (HAZOP) and the Hazard Identification (HAZID) procedures. The outcome of these procedures led to a number of actions including three tests that will be described below.

As the capability of the maximum torque detection procedure is one of the most safety critical parts of the valve manipulation operation, two important aspects of the torque level monitoring had to be investigated:

1) Maximum torque levels absorbed by the valve.
2) Long term changes and impairments on the torque level required to operate the valve.

In addition to these two tests that will be described in Sections V-A and V-B respectively, consequences of the worst case scenario implying a robot collision with a thin pipe should be empirically tested. These tests will be referred to as "crash tests" and will be the subject of Section V-C.

A. Maximum torque level tests

The test setup for finding the maximum torque level is reminiscent of the one used for the on-site demonstration in the sense that the same torque monitoring capability is used. This in particular implies that it is possible to set a threshold on the maximum allowable torque during the valve manipulation. The operation will then automatically stop if the torque applied to the valve exceeds this *a priori* chosen limit. As seen in Figure 6, the needle valve is being held in place using a vice, while a robot (ABB IRB4400 model) turns the valve until a given maximum torque limit is reached.

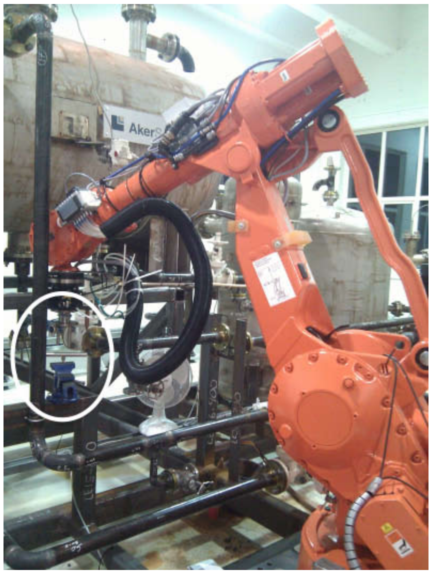


Fig. 6. The max torque test setup comprise an industrial robot that turns the same type of needle valves used during the on-site demonstrations.

The value of this max-torque-parameter is then increased successively until the valve has reached its physical limit upon which the top rod is destroyed. Figure 7 shows the final run while over-tightening one of the valves when the top rod of the valve broke. As seen from the figure, the top rod broke at approximately -85 Nm, a level which was exceeded in the previous run.

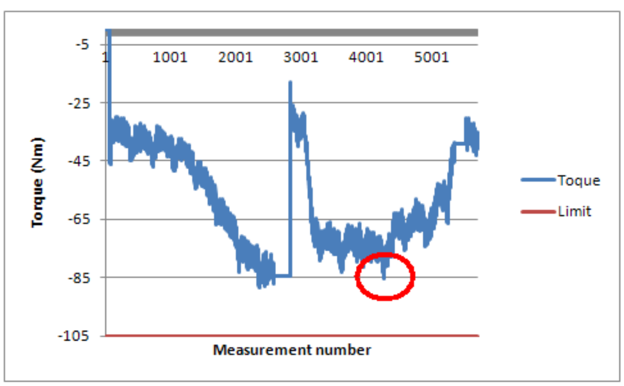


Fig. 7. Over-tightening a valve while having the maximum allowable torque limit set to -105 Nm (red horizontal line). The point where the top rod of the valve broke has been encircled.

B. Long term impairment tests

In order to investigate if the required level of torque to turn the valve changes over time, a test was conducted where the valve handle was turned 50 times back and forth while the torque was continuously monitored. The test results are shown in Figures 8-9 and clearly indicate that there is no sign of systematic change on the required level of torque to operate the valve.

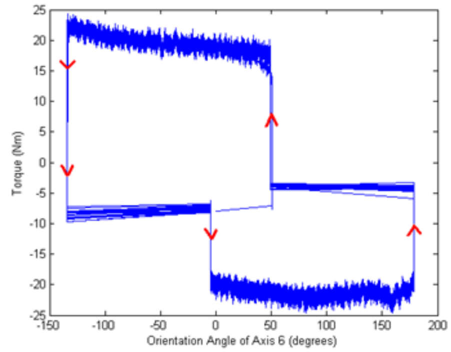


Fig. 8. During the long term impairment test, the valve was turned 50 times back and forth while the torque level was monitored. The red arrows indicate the direction of motion. As seen from the figure, no sign of characteristic changes in the valve could be found. An alternative representation of this result can be found in Figure 9.

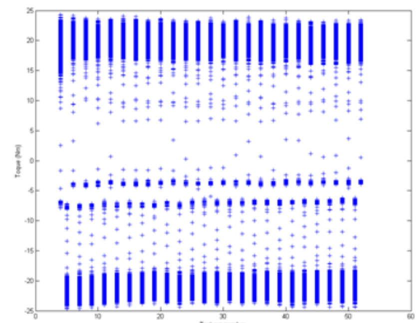


Fig. 9. An alternative representation of the results of the impairment test. Here, the 25 runs have been differentiated along the horizontal axis while the vertical axis depicts the required torque (in Nm). Here it is visually easy to confirm that the required level for turning does not systematically change over time as the valve is repeatedly turned back and forth.

C. Crash Tests

Another important safety measure that enables on-site robotic operations is the collision detection functionality of ABB robots. This built-in functionality which detects collisions in all directions and quickly ensures that the robot is stopped and slightly backed off from the point of collision, do no require any external sensors or mechanical devices. In order to verify the effect of the unlikely worst-case scenario when all other three independent layers of safety fail at the same time and the robot crashes with parts of the process equipment containing hydrocarbons, empirical tests on this fourth layer of reactive collision detection functionality had to be conducted. The main objective was to see how a 6 mm thin stainless steel pipe (the smallest dimension that existed within the robot's workspace on-site) would be affected if the robot crashed straight into it. The robot was instructed to move vertically across the horizontally mounted pipe with different speeds (up to 30 cm/s). Unaware of it's presence, the robot tool would then crash into the pipe. The setup and the result of this crash test can be seen in Figure 10, where it is notable that the 6 mm pipe is only mildly bent leaving it's isolating properties intact.

Fig. 10. The result of the crash test where the robot is run into a 6 mm thin pipe (red arrow) with a speed of 30 cm/s.

VI. Concluding remarks

Being aware of the level of robustness, accuracy and reliability required by the industry, this paper outlines a solution description relying on four independent layers of safety. In addition to the in-built reactive anti-collision layer, the SW and HW layers, our solution and design philosophy also comprise possibilities for the operator to halt or abort an operation at any time thereby keeping the remotely located human in the loop.

Both the operations described in this paper were requested by the current process operators. As such, they fulfill real automation needs found in the oil & gas industry. To the best of our knowledge, the valve manipulation operation reported in this paper, is also the first sensor-based robotic close-contact operation occuring in explosive atmospheres (ATEX) amidst a live hydrocarbon process. As previously noted, although actuated valves are widely used in the industry, the valve manipulation operation was found to include some of the most challenging subproblems of more general nature that were interesting to address. It is therefore notable that the solution concept described in this paper is also usable for other safety critical close-contact operations.

The demonstrations described in this paper have been installed on-site and run by the site operators for approximately four months. During that time, the valve turning operation has been successfully completed on a valve with live hydrocarbons tens of times, in all cases with the torque monitoring working as intended. The pictures provided by the thermal camera have turned out to be highly valuable to the flow assurance tests and the users have requested the feature to remain in future demos.

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