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Robot Automation in Oil and Gas Facilities: Indoor and Onsite Demonstrations

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***Abstract*— Given the importance and focus of the oil and gas industry *related* to safety, environmental impact, cost efficiency and increased production, the potential for more extensive use of automation in general, and robotic technology in particular, is evident. The specific role of robots in this context will be to perform various inspection and manipulation operations which human field operators perform today. In this paper, we initially present an overview of the current trends and challenges within the oil and gas industry. This is followed by the latest results from our work towards realizing next generation robotized oil and gas facilities. These activities encompass indoor lab experiments, as well as outdoor demonstrations onsite. The onsite demonstration reported in this paper has been completed together with Shell and comprises the world's first prototype of a robot performing automatic scraper handling in real operational environments.**

I. Introduction

ALTOUGH alternative energy sources are expanding, due to the growing energy consumption world-wide, the need for oil and gas remains high for the foreseeable future. The oil and gas industries are however facing a number of challenges. As a general trend, most of the easy accessible oil and gas fields have already been exploited, leaving the more remote and geo-politically challenging reserves for future exploration. Depending on domain of operation, challenges are particularly found in the desert, offshore, deep water and in the Arctic. To cope with this, the oil and gas industries are continuously looking towards novel technical solutions, working practices and business models. The main drivers are to improve health, safety and environment (HSE), as well as production and cost efficiency. More recently, the oil and gas industry has paid attention towards utilizing robotics technology as an enabler to perform remote inspection and maintenance of their facilities. By relocating the humans from remote, harsh and unpredictable sites with potentially poisonous atmosphere, to more conveniently located control rooms, dramatic improvements in HSE as well as business value are foreseen. This allows extension of the lifetime of existing facilities (upon renovation) while making development of new marginal fields affordable.

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A. ABB's Role, Design Philosophy and Roadmap

Studies conducted in collaboration with customers show that complete automation of oil and gas facilities require solution of more than 1000 different operations that are performed today by on-site staff. With this figure in mind, it becomes clear that both robotic technology and dedicated hard-automation have to be combined in order to choose the most suitable solution for each individual operation. Important aspects to consider in this selection process primarily include cost and complexity issues.

As a global provider of power and automation systems as well as one of the leading robot manufacturers in the world, ABB has recognized the need for higher degree of automation as a way to reduce HSE risks. Combining this with the know-how and over 50 years of experience from oil and gas, puts ABB in a unique position to develop the next generation of robot automated facilities. Our design philosophy is founded in the fact that the (remotely located) operator does not need yet another technical system to learn and to deal with. Therefore, the robots are seen as assets in the control system which are used as the remote field operator's ”eyes, ears and hands” [1]. This gives a clear focus on keeping humans in the loop, not to put people of, but relocating them to a safe location from where they can interact with the robotic system. The interaction occurs through the human robot interface (HRI) of the control system by defining and initiating different tasks which the robot is expected to complete flawlessly. The control system then returns and presents results of the task to the remotely located operator. The human operator will also define and initiate any unexpected task that has not been accounted for. The degree of autonomy in a deployed robotic system will hence vary from manual remote control (an unforeseen task which the operator needs to define), through semi-autonomous, to autonomous control, where the human operator is not involved in the task execution at all. In this setting, whenever possible, the robot itself is eliminated from the operator interface.

Our strategy is further 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. 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 sites. This strategy of stepwise maturing of the technology is not only positive from a technical point of view. Demonstrating the readiness of the technology also raises the awareness within our partners' organizations and builds confidence in the technology as such and in ABB as a supplier.

B. *Related Work*

Developing a reliable and intelligent robotic system, which enables the operation of normally unmanned oil and gas facilities, requires solving a number of challenging sub-problems. Aspects that need particular attention include operator interface and control room visualization [2,3], high-level robot allocation and task scheduling [4,5,6,7,8], safe human-robot interaction and collision handling [9,10,11,12,13,14], motion planning [15,11], safety and reliability of the SCADA control networks [16,17,18,19], camera viewpoint planning and 3D mapping [20,21,22] and telerobotics [23,24]. In addition to this, the harsh and potentially explosive environment requires all hardware, *e.g.*, the robot manipulator, tools and sensors, to satisfy the ATEX[1] criteria and be approved for the harsh weather conditions. These constraints drastically limit the available hardware on the market.

Nevertheless, one must bear in mind that even if all these sub-problems were solved in a satisficing manner, system integration would still remain a grand challenge. Work in this direction includes robotic prototypes for industrial maintenance and repair applications [25]. Other research efforts on building functional prototypes of outdoor robots include domains such as agricultural robots [26,27], animal-farming [28,29], mining [30] and power plants [31,32]. However, as stated previously and witnessed in [33], 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.

Two other research groups working with robotic technology specialized to the needs of the oil and gas industry are Fraunhofer and SINTEF. Stuttgart based 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 [34,35]. On the other hand, SINTEF ICT has developed and tested various system components in their indoor lab facility located in Trondheim, Norway [36]. Preparing the system for harsh environmental conditions has however not been a dominant part of SINTEF's agenda so far.

II. Indoor Test Facility

Our R&D unit possesses an indoor test facility to explore, develop, test and evaluate solutions that could be of interest for future oil and gas facilities. The laboratory comprises three ABB robots (one gantry-mounted IRB2400 and two rail-mounted IRB4400s) and a full-scale separator process module. All robots have access to multiple tools that can be changed automatically using pneumatic tool changers. Some of the sensors are carried on the robot arm itself, such as cameras for monitoring the work, whereas application specific sensors are mounted on the tools. The valve manipulation tool depicted in Figure 3 (right), serves as an example of such.

Figure 1 outlines the system layout of the test facility. The robots are controlled by the robot controllers, and a control system controls the process. All these controllers are accessible from an application server. The application server runs path planning algorithms and handles the communication with the users. One of its main tasks is to translate the commands given by the users to instructions for the controllers.

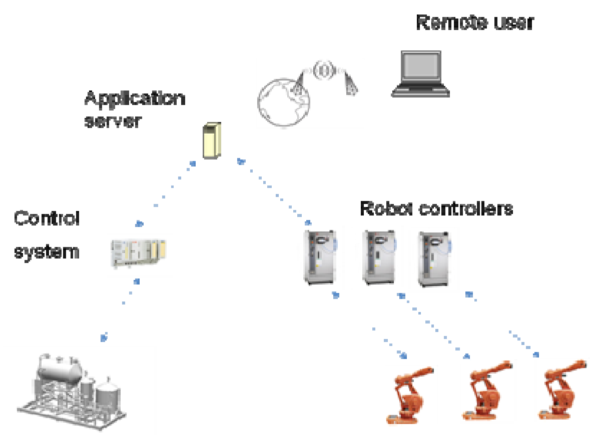

Figure 1 Robotics system architecture.

Three main aspects of telerobotics are tested in the lab. These are autonomous control, semi-autonomous control and manual remote control. During semi-autonomous control, the control system or the operator initiates tasks for the robots. The (remotely-located) expert utilizes a 3D process model as the interface to the process to define and initiate tasks for the robots and to retrieve the results from such tasks. This has been tested by operating the test facility remotely from various locations, including Houston and Stavanger. The tests have proven that the technology works consistently over several days, even over a public network with limited bandwidth.

In harsh environments, instruments and apparatus can move or get mechanically deformed, temporarily or permanently. Hence, the position and orientation of these objects are not fixed and constitute an uncertainty that needs to be taken into account when the robots interact with the process. In our indoor test facility, computer vision and optimization algorithms have been used to cope with these uncertainties.

In this paper, results from a demonstration of sensor-based valve manipulation are presented. This particular demonstration involves two collaborating robots. The first is equipped with a standard network camera with resolution 640 by 480 pixels (Figure 3 (left)) and the second with a specially designed tool for valve manipulation (see Figure 2 and Figure 3 (right)). The camera equipped "inspection robot" extracts the exact position and orientation of the valve

[1] The abbreviation derives from the French title: Appareils destinés à être utilisés en **AT**mosphères **EX**plosibles.

based upon computer vision and optimization techniques, after which it sends them to the second robot which moves in and manipulates the valve.

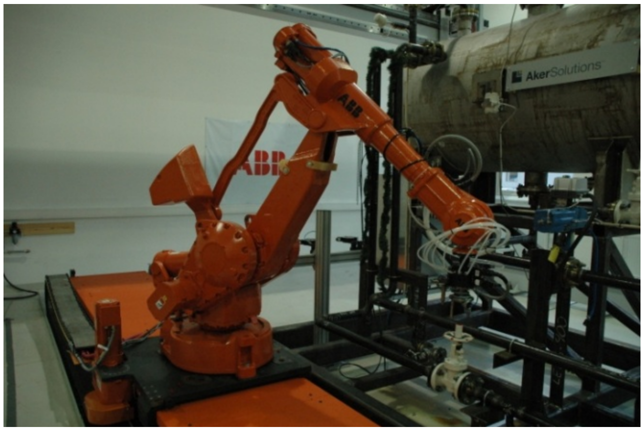

Figure 2 ABBs IRB4400 robot with tool changer and valve manipulation tool.

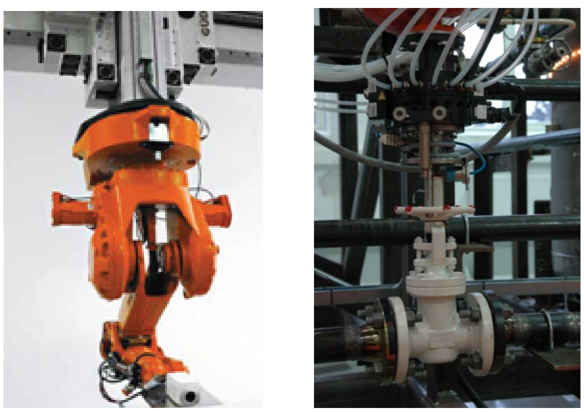
Figure 3 (Left): Inspection robot equipped with a network camera. (Right): Valve manipulation tool attached to the robot through the pneumatic tool changer.

Hence, step one in locating a valve is to move the inspection robot into an entry position, defined such that the target is visible somewhere in the camera's field of view. By analyzing an acquired camera frame, the center point of the valve, p_c, and six reference points p_i, i = 1, ... , 6, equally spaced around the valve wheel are found (see red knobs on the wheel depicted in Figure 4).

Next stage is to iteratively move the robot with an optimization algorithm so that p_c appears in the center of the camera frame. Let

$$d_i = | p_i - p_c |, i = 1, \cdots, 6,$$

measured in pixels, and compute the average,

$$d = \frac{1}{6} \sum_{i=1}^{6} d_i.$$

To find the orientation and hence, to be able to align the camera in front of the valve, the robot is moved iteratively with the objective to

$$\text{minimize} \sum_i (d_i - d)^2.$$

Due to the low camera resolution and the initial distance between the camera and the valve, it is recommended to continuously approach the valve in a step-by-step fashion and for each step, to repeat the procedure above until a certain stop criterion is reached. For instance, $d > d_{ub}$, where d_{ub} is a preset upper bound for the distance between p_c and any given p_i. In our case, d_{ub} has been chosen based on a relation between pixel error and position inaccuracy.

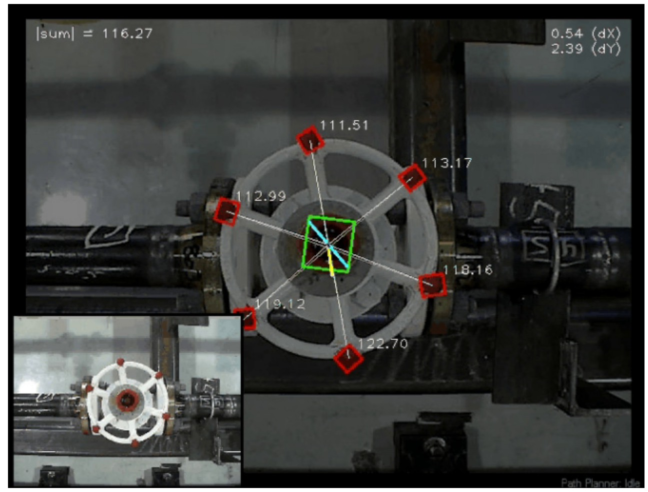

Figure 4 A robot equipped with a standard low-resolution network camera, determines the exact position and orientation of the valve using computer vision and an gradient based optimization algorithm.

Once the inspection robot has determined the position and orientation of the valve with sufficient level of accuracy and sent them to the second robot, it moves to a view-point providing the remote operator visual overview of the valve. The second robot then automatically picks up the associated valve manipulation tool and move towards the valve. To further enhance robustness, a proximity switch is used in order to determine when the tool has reached appropriate horizontal level to allow safe turning of the valve. Upon completion, the valve manipulation tool is put back in the tool shed after which both robots return to their home positions.

With this approach, sub-millimeter accuracy has been achieved successfully in all of the more than 50 experimental runs performed in the lab. This accuracy level is well inside the maximum allowed deviation of 2 mm which origins from hardware restrictions on the designed valve manipulation tool.

III. Onsite Demonstrator

This section presents an onsite demonstrator of scraper handling which was performed as a collaborative project between ABB and Shell Global Solutions. The purpose of the project has been to demonstrate the use of robotics technology for handling scrapers in real process environment. A scraper is a device that is sent through a pipeline to inspect or clean the inside of the pipe. Such devices have elastic, over-dimensioned disks, which seal against the pipe while the pressure from the transported product behind the scraper pushes it forward. Scrapers are inserted and extracted at special stations along both oil and gas pipelines. Today, launching and receiving of scrapers are generally manual operations. It is a dirty and heavy job which also represents a certain risk for the human operator. While traveling through the pipeline, the scraper will accumulate debris. At the receiving end, the pipeline is widened into what is called a trap, or a barrel, to catch the scraper. This barrel needs to be depressurized and drained before the door into the barrel can be opened and the scraper extracted. The accumulated debris sometimes makes the depressurization fail, in which case the scraper can be ejected with great force. Several incidents have been reported where operators have been injured during this operation. In addition, in facilities with a high degree of poisonous gas in the reservoir, often referred to as sour gas facilities, scraper handling operations are surrounded by very strict procedures, making these operations undesired both from cost and HSE perspective.

With the main driver of reducing the HSE risks in sour gas facilities, ABB and Shell have collaborated to prove that a robot can perform scraper handling operations. An ATEX certified industrial ABB robot (IRB5500) has been used for the demonstration. The robot has been equipped with a tool specifically designed for scraper handling. The tool includes sensors to guide the robot and to verify that operations can be performed safely. A standard scraper barrel and door was used, without any modifications to ease the automation. The robot has been controlled by an operator interface next to the robot. To secure a high focus on safety, a trained operator has been responsible for acknowledging each step of the execution before allowing the robot to continue with the subsequent step.

The site used for the demonstrator installation was NAM Schiedam's facility Gaag outside Rotterdam, the Netherlands. This site cannot be said to have a very extreme climate, but with the demonstrator taking place during the winter, the temperature occasionally dropped down to minus 10 degrees Celsius and the robot where tested in both snow, rain and sunshine (see Figure 5).

At Gaag, the robot has been installed at a scraper receiver (trap). The robot is first to verify that initial safety critical preparation steps have been executed by ensuring that the door lock and handle are in the expected locations (locked and closed). This is done using a proximity switch integrated into the tool. From this starting point, the robot unlocks and opens the barrel door to allow debris and residue oil to pour onto a drain table in front of the barrel. The robot inserts the tool into the barrel and searches for the scraper. The tool compromises a proximity switch that indicates the presence of a scraper in front of the tool. The search is performed with inbuilt functionality in the robot controller to stop the movement on state change of an input signal. When the scraper is found, the robot extracts the scraper and places it on the table. The door is then closed and locked before the robot returns to its home position.

Some limitations were imposed on this demonstrator to fulfill the requirements. The number of robotized tasks related to the scraper operation made up a subset of the complete operation of scraper receiving. The complete operation to receive a scraper includes opening and closing of valves, running drain pumps and removing vent plugs, after which the scraper extraction task starts. All these steps can however be automated with existing technology but this has not been within the scope of the project. Also, the robotics demonstrator could retrieve scrapers which were located relatively close to the door (<0.5 m). In reality, the scrapers may be located between 0-2 meters from the door. Finally, the demonstrator was powered with a standalone diesel generator and produced its own instrument air, to avoid major modifications to the plant drawings.

Figure 5 The ATEX certified ABB IRB5500 robot at the scraper station on a cold day during the demonstration period.

Figure 6 The robot performing its scraper handling task onsite.

During the demonstration period, the application was to extract the scrapers from the trap. This was depending on the nature of the site, where they receive but don't launch scrapers. In laboratory environment, the robot has been used to insert the scrapers into the barrel as well, which is easier than receiving in a real situation, since the scrapers are clean when launched.

For the demonstrator, no modifications were made on the barrel or the door, but to make a cost efficient solution, the barrel should be designed for robot automation. Designing the robot, tool and barrel as one interconnected system is expected to give even more robust solutions and is seen as the natural extension in the development of a commercial system.

With this onsite demonstrator operating on a real site in an outdoor environment regardless of the weather conditions, ABB and Shell together have taken a significant step in showing that robots can be used at oil and gas facilities to perform operations requiring both high precision and strength. This demonstrator has successfully validated that robots can be used particularly for scraper handling, and hence, reduce today's HSE risks.

IV. Concluding Remarks

The oil and gas industry is facing a number of challenges in the coming years, and these must be tackled by innovative and novel technical solutions and the development of new business models. Future robotized oil and gas facilities represent a major opportunity in this context with the main goal of improved HSE, as well as production- and cost efficiency.

Nevertheless, although robotic systems can take over most of the repetitive, dangerous, heavy and dirty jobs, they can rarely do the entire job without involving people in the loop. This is partly due to the unpredictable and uncertain nature of the surrounding environment, which may include unforeseen tasks. Recognizing this paradigm, the robots are seen as assets in the control system which are used as the remote field operator's "eyes, ears and hands". This paradigm also raises the operator's situational awareness which is of great importance in case of malfunction recovery.

This paper presents the current status of our work towards realizing the next generation robotized oil and gas facilities. Our roadmap is based on a step-by-step approach involving development and validation of the technology in more and more demanding settings. These activities encompass tests in our indoor test facility as well as outdoor demonstrations onsite.

The indoor lab is mainly used in an extensive R&D project between ABB and Statoil. In this setting, we have successfully performed various inspection operations and can now, for the first time, report demonstration results, where sensor-based close-contact operations, such as valve manipulation, are performed.

This paper also includes details about recent onsite demonstrations where ABB and Shell have developed the world's first prototype of a robot performing automatic scraper handling in real operational environments. This demonstration has been run successfully over 30 times on the site during the pilot period

Near-future work and development include performing wireless vibration monitoring of various process equipment indoors, as well as outdoor demonstration of remote inspection capabilities.

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