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A step-wise approach to oil and gas robotics ⋆

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Abstract: Developing a reliable and intelligent robotic system which enables the remote operation of normally unmanned oil and gas facilities requires innovative and novel technical solutions. Our strategy for meeting these challenges is based on a step-wise 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 further developed, 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. In this paper, this design philosophy is elaborated upon and illustrated using the development of a valve manipulation application as an example.

Keywords: Industrial Automation, Outdoor Robotics, Field Robots, Autonomous Robots, Remote Operation, Human-Machine Interaction, Oil and Gas Industry

1. INTRODUCTION

Given the importance and focus of the oil and gas industry on safety, environmental impact, cost efficiency and increased production, the potential for more extensive use of automation in general, and robot technology in particular, is evident. In recent years, the oil and gas (O&G) industry has begun to explore the potential of robotics, the main drivers being to improve health, safety and environment (HSE), as well as production and cost efficiency. There are increased risks associated with O&G operations, *e.g.*, in offshore production facilities and fields with the presence of toxic sour gases. Robots can be designed to work 24/7, are reliable and flexible and can work in hazardous, harsh and dirty environments. Within the O&G segment, robots have only been used sporadically so far. Examples of applications are ROVs, automation of drilling operations and intelligent pigs. The applications generally stand out from other industries as the main driver has been to automate tasks that have been difficult or even impossible for people to undertake based on HSE issues. Applying robotics in this way has resulted in an improvement in HSE but often with an associated dip in production. Although this is contradictory to the general goal of automation, work is now focusing on maintaining focus on HSE and at the same time improving efficiency and profitability of the facilities.

O&G installations put strong demands on the robot systems technology regarding design and requirements. In addition to being ATEX-certified [1], robots and related equipment (*e.g.*, tools and sensors) will have to be approved for harsh weather conditions. They have to tolerate extreme temperatures, strong wind, humidity, salt water, sand and potentially, snow and ice. Not all of these conditions may be present at each site, but the environment in typical O&G facilities are extremely harsh and tough on the equipment. The deployed hardware will for instance have to be resistant to water, *i.e.*, Ingress Protection class 67 or higher, and to be protected for corrosion from salt water sprays.

2. RELATED WORK

A number of challenging subproblems need to be adressed in order to deliver a reliable and intelligent robotic system which enables the remote operation of normally unmanned oil & gas facilities. Aspects that need particular attention include operator interface (Heyer, 2010), control room visualization (Goodrich and Schultz, 2007), high-level robot allocation and task scheduling (Haupt, 1989; Li and Womer, 2009), camera viewpoint planning and 3D mapping (Tarabanis et al., 2009; Scott et al., 2003), telerobotics (Sheridan, 1995), safe human-robot interaction and collision handling (Haddadin et al., 2007; Kuhn and Henrich, 2007; Cheung and Lumelsky, 1989), safety and reliability of the SCADA control networks (Igure et al., 2006; Alcaraz-Tello et al., 2008) and motion planning (Lozano-Perez, 1987; Cheung and Lumelsky, 1989).

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 (Parker and Draper, 1999). Other research efforts on building functional prototypes of outdoor robots include domains such as agricultural robots (Henten et al., 2002; Åstrand and Baerveldt, 2002), animal-farming (Andersen et al., 2005),

⋆ Contribution to invited session on Robot Automation in Explosive Oil & Gas Environments.
[1] The abbreviation derives from the French title: Appareils destinés á être utilisé s en ATmosphéres EXplosibles.

mining (Gary and Stentz, 1992) and power plants (Abidi et al., 1991). However, as stated previously and witnessed in Virk (1997), 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 manipulation objectives described in Abidi et al. (1991) are reminiscent of those described in this paper, the 90% success-rate is clearly below the acceptance rate for real-world deployment in O&G facilities amidst live hydrocarbon pipes.

Three other research groups working with robotic technology specialized to the needs of the O&G industry are Fraunhofer IPA, SINTEF ICT and NREC at Carnegie Melllon University. 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 (Graf et al., 2007; Graf and Pfeiffer, 2008). SINTEF ICT has developed and tested various system components in their indoor lab facility located in Trondheim, Norway but preparing the system for harsh environmental conditions has however not been a part of SINTEF's agenda so far (Kyrkjebø et al., 2009). In clsoe collaboration with Shell, NREC have designed "Sensabot" a remotely controlled demonstrator platform for inspection and monitoring of various industrial facilities (Sensabot, 2012). The Sensabot platform is however not designed to cope with maintenance and intervention operations that imply close contact with the process equipment.

3. DESIGN PHILOSOPHY AND ROADMAP

Studies conducted in collaboration with customers show that complete automation of O&G 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. 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 and used as the remote field operators "eyes, ears and hands" (Skourup and Pretlove, 2009). 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 machine interface (HMI) of the control system by defining and initiating different tasks which the robot is expected to complete flawlessly (see Figure 1). 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.

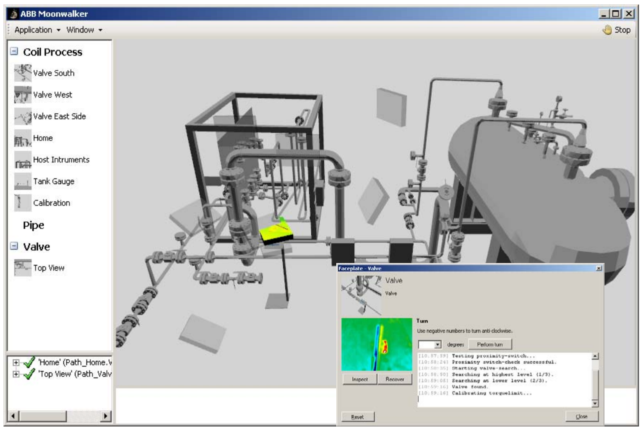


Fig. 1. Screen shot from the HMI.

Our roadmap strategy is further based on a step-wise 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 O&G 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.

The rest of the paper is organized as follows. The three subsequent steps in our development strategy are explained more thoroughly in Section 4 (indoors), Section 5 (outdoors) and Section 6 (on-site), respectively. In all these sections, the reader is guided through a particular case study, namely the development of a robot system used for autonomous valve manipulation operation. Finally, conclusions and outlook towards future work is provided in Section 7.

Before embarking however, it should be noted that although actuated valves are frequently used in the industry, developing a robotic valve manipulation application was nevertheless considered as it 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 on-line generation of safe movements while performing high-accuracy, close-contact operations.

4. INDOOR TEST FACILITY

The indoor robot test facility is normally the first step for exploring, developing, testing and evaluating solutions that could be of interest for future oil and gas facilities. New concepts, algorithms, application demonstrators and sensor technologies are initially tested here since it represents a controlled test environment where individual parameters can be changed relatively easy. Some demonstrators are developed and demonstrated in this lab with the main purpose to demonstrate a new concept whereas others follow a technology readiness process preparing them for outdoor, onsite deployment.

The indoor test facility comprises three ABB robots (one gantry-mounted IRB2400 and two rail-mounted IRB4400s) and a full-scale separator process module as seen in Figure 2. 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(b), serves as an example of such.

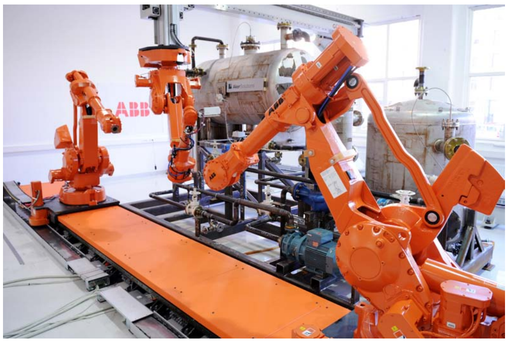


Fig. 2. The ABB indoor test facility in Oslo, Norway.

In this paper, results from a indoor demonstration of sensor-based valve manipulation are presented. This particular demonstration utilizes tools from computer vision and optimization and involves two collaborating robots. The first is equipped with a standard network camera with resolution 640 by 480 pixels (Figure 3(a)) and the second with a specially designed tool for valve manipulation (Figure 3(b)). The camera equipped inspection robot extracts the exact position and orientation of the valve based upon computer vision and optimization techniques, after which it sends them to the second robot which moves in and manipulates the valve.

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, $i = 1, \cdots, 6$, 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. To this end, let

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

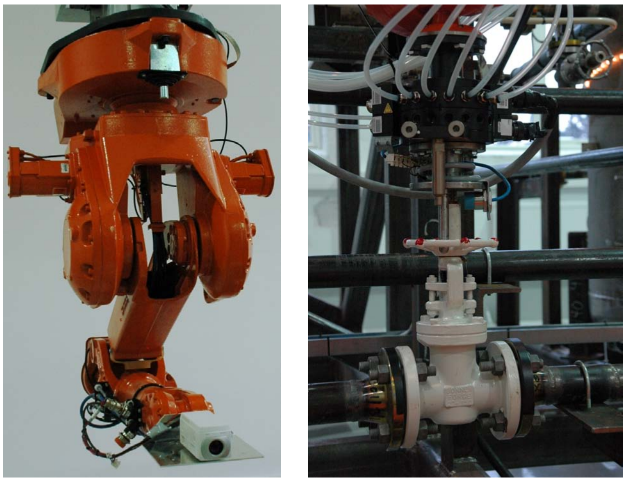
measured in pixels, and compute the average,

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

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.



(a) Inspection robot (b) Valve manipulation tool

Fig. 3. The indoor valve manipulation demonstration involves two collaborative robots. The first one is camera equipped and used for extracting exact position and orientation of the valve while the second holds a specially designed tool enabling valve manipulation.

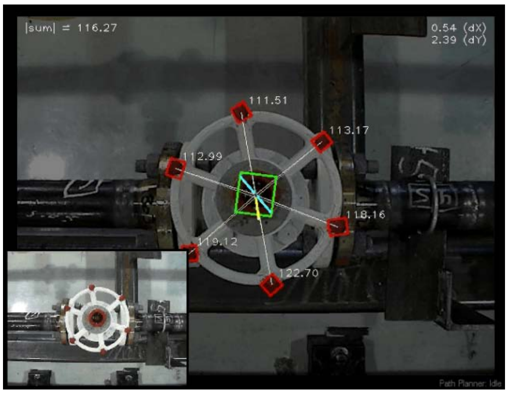


Fig. 4. A robot equipped with a standard low-resolution network camera, determines the exact position and orientation of the valve using computer vision and an gradient based optimization algorithm.

With this approach, sub-millimeter accuracy is achieved which is well inside the maximum allowed deviation of 2 mm originating from hardware restrictions on the designed valve manipulation tool. However, the reliability and robustness of the computer vision based algorithm was not satisfactory when taking various lighting conditions into account. Hence, based on the experiences gained during the indoor tests, some pivotal changes were made to the suggested sensor setup, hardware configuration and solution algorithm before continuing with the developments outdoors. This will be elaborated upon in the next section.

5. OUTDOOR TEST FACILITY

One of the main objectives when setting up the outdoor test facility has been to minimize the deployment and comissioning time for on-site demonstrations. In fact, before taking an application demonstrator to a real O&G facility, it normally has to pass a Factory Acceptance Test (FAT) taking place at the outdoor test facility. To achieve this level of compatibility, most of the constraints found on-site are imposed on the outdoor tests as well. For instance, environmental constraints, such as ATEX-certification and adequate Ingression Protection (IP) rating, are normally imposed. To this end, an ATEX-certified ABB robot (IRB5500) with IP67 protection degree has been installed in our outdoor test facility in Oslo(Figure 5.

Fig. 5. The outdoor test facility enables testing in more realistic environments. Most prominently, the effect of various weather- and lighting conditions must be taken into account. To minimize the deployment gap between the outdoor tests and on-site demonstrations, an ATEX-certified ABB robot (IRB5500) is utilized.

The objective to mimic the on-site environment goes beyond hardware requirements by encompassing software components such as robot controller configuration, 3D world model and cohesive Human Machine Interface (HMI) used for initiating, controlling and supervising operations (see Figure 1).

As previously mentioned, based on the experiences gained during the indoor tests with valve manipulation, a number of vital changes were made while preparing the demonstration for the next step outdoors. Firstly, it was concluded that by designing a specialized tool comprising sensors and a spring suspended valve manipulation device, the entire operation could be handled using only one robot. Secondly, the design of the valve handle was drastically modified. The valve handle used indoors and depicted in Figures 3(b) and 4 are primarily designed for human intervention. To ease robotic manipulation, the valve handle was turned into a simple rod as seen in Figure 6. Finally, the network vision camera used indoors was changed to a thermal camera that allowed "seeing" the valve handle in the face of various weather- and light conditions (see Figure 7). This decision was a direct consequence of the shortcomings and lack of robustness witnessed during the tests performed indoors.

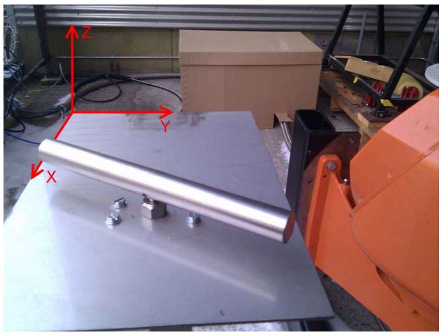


Fig. 6. The exact rotation of the valve handle in the xy-plane and the vertical position of the valve (z-coordinate) are not known *a priori* and hence must be accurately and robustly detected. The accuracy requirements on the operation is set to $\pm 1°$. The provided solution is considered to be successful as long as it is accurate enough, perfectly safe, flawlessly performed and takes a couple of minutes to complete.

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 6). 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 increase the reliability of the proposed solution even further, it was also decided to sense the exact position of the valve handle using an inductive proximity switch. Although this detection procedure is extremely reliable and has been flawlessly performed at all instances, the spring suspension in the valve manipulation device 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 designed robot tool seen in Figure 8 holds the ATEX certified thermal camera, proximity sensor and the valve manipulation device.

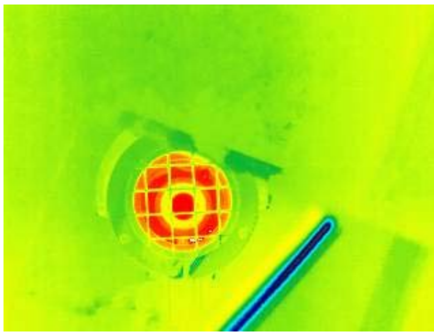


Fig. 7. The valve handle (blue rod) as seen through the thermal camera image.

To 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

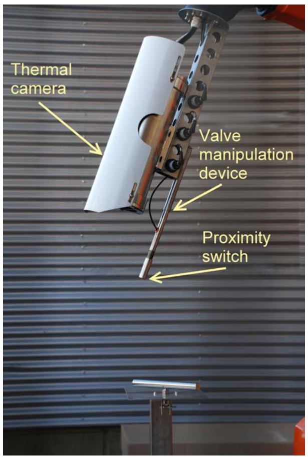


Fig. 8. The tool comprising ATEX-certified thermal camera, sensors and valve manipulation device.

angle was developed. For our practical purposes, a 10^{th} degree polynomial was found to be accurate enough. 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 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

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

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.

Having put the proposed torque overload detection scheme at comprehensive testing including the FAT procedures, we are now ready for the next step: on-site installation. This is the topic of the next section.

6. ON-SITE DEMONSTRATOR

The third and final step is to set up, demonstrate and test the application demonstrator in a real oil and gas environment. Such demonstrators take place in close collaboration with customers and at their sites.

Before being granted permission to perform sensor-based robotic valve manipulation on-site amidst live hydrocarbons, a number of safety related issues had to be investigated and addressed. To begin with, as part of the standard safety procedures of the O&G industry, 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. These are industry wide adopted tools and methods for identifying potential safety and operational problems associated with the design or operation of a new system.

Meeting the extremely high demands on safety and robustness imposed by the O&G industry, may fall outside the traditional boundaries for most researchers and developers. Our proposed robotic solution relies on four independent layers of safety measures. The first layer consists of the collision detection functionality of ABB robots. It is notable that this in-built functionality do no require any external sensors or mechanical devices but detects collisions in all directions and quickly ensures that the robot is stopped and slightly backed off from the point of collision. In addition to this reactive anti-collision layer, the software and hardware layers, our solution and design philosophy also comprise possibilities for the operator to overview and halt or abort an operation at any time thereby keeping the remotely located human in the loop.

Fig. 9. The valve manipulation operation has been performed successfully tens of times on-site.

The automatic valve manipulation demonstrator described in this paper was installed at K-lab which is a meetering and technology laboratory located at Statoil's Kårstøprocessing plant on West Coast of Norway (Figure 9). Once installed on-site, it was run by site operators for approximately four months. During this period, the valve turning operation was successfully completed on a valve with live hydrocarbons tens of times and in all cases the torque monitoring worked as intended.

7. CONCLUSIONS AND FUTURE OUTLOOK

The development of robot systems for remote inspection and intervention requires a breakdown into smaller, standalone applications that can be implemented, tested and verified separately before being integrated into a larger system. A number of application demonstrators has already been implemented and tested in live processes with hydrocarbons. Common to these applications are that current site operators have requested the specific operations. As such, they fulfill real automation needs found in the O&G industry today.

The automatic valve manipulation application described in this paper is an example of a close-contact operation and involves sensor-based movements implying that the robot paths have not been offline programmed. This is in contrast with the traditional approach for industrial robots. To the best of our knowledge, the valve manipulation operation is 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 more challenging subproblems of more general nature that were interesting to address. These include but are not limited to the design of the HMI and on-line generation of safe movements while performing high-accuracy, close-contact operations. It is therefore notable that the solution concept described in this paper is also usable for other safety critical close-contact operations.

Future robotized oil and gas installations represent a major opportunity for the industry with the main goal of improved HSE, as well as decreased downtime due to a better understanding of the continuous health of the process equipment. 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 and used as the remote field operators eyes, ears and hands. This paradigm also raises the operators situational awareness which is of great importance in case of malfunction recovery. Near-future work and development include to prove technology readiness and to build confidence in the technology with different stakeholders such as site operators, process engineers and management.

REFERENCES

Abidi, M., Eason, R., and Gonzalez, R. (1991). Autonomous Robotic Inspection and Manipulation Using Multisensor Feedback. *Computer Journal*, 24(4), 17–31.

Alcaraz-Tello, C., Fernandez-Navarrete, G., Roman-Castro, R., Balastegui-Velasco, A., and Lopez-Munoz, J. (2008). Secure management of SCADA networks. *New Trends in Network Management*, 9(6), 22–28.

Andersen, N., Braithwaite, I., Blanke, M., and Sorensen, T. (2005). Combining a novel computer vision sensor with a cleaning robot to achieve autonomous pig house cleaning. In *Proc. of the* 44^{th} *IEEE Conference on Decision and Control (CDC)*, 8831–8336. Seville, Spain.

Åstrand, B. and Baerveldt, A. (2002). An agricultural mobile robot with vision-based perception for mechanical weed control. *Autonomous Robots*, 13(1), 21–35.

Cheung, E. and Lumelsky, V.J. (1989). Proximity sensing in robot manipulator motion planning: system and implementation issues. *IEEE Transactions on Robotics and Automation*, 5(6), 740–751.

Gary, S. and Stentz, A. (1992). A robotic system for underground coal mining. In *Proc. of the IEEE International Conference on Robotics and Automation (ICRA)*, 633–638.

Goodrich, M. and Schultz, A. (2007). Human-robot interaction: A survey. *Foundations and Trends in Human-Computer Interaction,*, 1(3), 203–275.

Graf, B. and Pfeiffer, K. (2008). Mobile robotics for offshore automation. In *Proc. of the IARP/EURON Workshop on Robotics for Risky Interventions and Environmental Surveillance*.

Graf, B., Pfeiffer, K., and Staab, H. (2007). Mobile robots for offshore inspection and manipulation. In *Proc. of the International Petroleum Technology Conference (SPE)*.

Haddadin, S., Albu-Schäffer, A., and Hirzinger, G. (2007). Safety evaluation of physical human-robot interaction via crash-testing. In *Robotics: Science and Systems Conference*, 217–224.

Haupt, R. (1989). A survey of priority rule-based scheduling. *OR Spectrum*, 11(1), 3–16.

Henten, E.V., Hemming, J., Tuijl, B.V., Kornet, J., Meuleman, J., Bontseman, J., and Os, E.V. (2002). An autonomous robot for harvesting cucumbers in greenhouses. *Autonomous Robots*, 13(3), 241–258.

Heyer, C. (2010). Human-robot interaction in future industrial robotics applications. In *Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 4749–4754. Taipei, Taiwan.

Igure, V., Laughter, S., and Williams, R. (2006). Security issues in SCADA networks. *Computers & Security*, 25(7), 498–506.

Kuhn, S. and Henrich, D. (2007). Fast vision-based minimum distance determination between known and unknown objects. In *IEEE International Conference on Intelligent Robots and Systems (IROS)*. San Digeo, CA, USA.

Kyrkjebø, E., Liljebäck, P., and Transeth, A.A. (2009). A robotic concept for remote inspection and maintenance on oil platforms. In *Proc. of the ASME* 28^{th} *International Conference on Ocean, Offshote and Arctic Engineering*. Honolulu, Hawai.

Li, H. and Womer, K. (2009). Scheduling projects with multi-skilled personnel by a hybrid MILP/CP benders decomposition algorithm. *Journal of Scheduling*, 12(3), 281–298.

Lozano-Perez, T. (1987). A simple motion planning algorithm for general robot manipulators. *IEEE Journal of Robotics and Automation*.

Parker, L. and Draper, J. (1999). Robotics applications in maintenance and repair. In *Handbook of Industrial Robotics, 2nd Edition*. Wiley.

Scott, W., Roth, G., and Rivest, J. (2003). View planning for automated three-dimensional object reconstruction and inspection. *ACM Computing Surveys*, 35(1), 64–96.

Sensabot (2012). `http://www.rec.ri.cmu.edu/projects/shell`. Accessed 2012-03-27.

Sheridan, T. (1995). Teleoperation, telerobotics and telepresence: A progress report. *Control Engineering Practice,*, 3(2).

Skourup, C. and Pretlove, J. (2009). The robotized field operator. *ABB Review*, (1), 68–79.

Tarabanis, K., Allen, P., and Tsai, R. (2009). A survey of sensor planning in computer vision. *IEEE transactions on Robotics and Automation*, 11(1), 86–104.

Virk, G. (1997). Industrial mobile robots: the future. *Industrial Robots*, 24(2), 102–105.