Human-Robot Interaction and Future Industrial Robotics Applications

Clint Heyer

Abstract— **Industrial robots, designed for performing operations quickly, repeatedly and accurately have a long heritage in the manufacturing industry, operating in relatively static environments and in large numbers. Trends in the oil and gas industry to improve safety and efficiency and reduce environmental impact suggest the use of industrial robotics. New developments in regions difficult or dangerous for humans to work in could be enabled with maintenance, inspection and repairs carried out by remotely-controlled industrial robots. This new application area highlights some difficulties with today's robots, as they do not adapt well to dynamic environments, do not offer rich human-robot interaction and are not simple for end-users to program. In addition, the oil and gas context presents a challenging work environment for robots as they are exposed to variable and often extreme weather and need to be safe for use alongside explosive hydrocarbons. As robots are introduced, issues of trust and accountability come to the fore as well as how they fit into organisational structures. If robots have too little autonomy, human operators will waste time attending to robots instead of attending to their work tasks. If robots are highly autonomous, situational awareness of plant activity is diminished. A balance needs to be struck to find a level of autonomy suitable for the task, the realistic capabilities of the automation, and the need to actively engage human operators in a constructive fashion. These issues also relate to what form the interface takes for remote or co-located robot control, as well as how information and activity is represented for remote operators. The contribution of this paper is a discussion of issues relating to human-robot interaction for future industrial robotics, in particular for the oil and gas industry.**

I. INTRODUCTION

Industrial robots have been well-established in the manufacturing sector for over thirty years, employed for tasks such as stacking, casting, painting, sorting, welding, component soldering and so on. This use context highlights the core value proposition of an industrial robot: performing tasks continuously and accurately in work environments and scales difficult for humans. During the commissioning of a factory or when the line is being re-tasked, specialist engineers program the robots for their forthcoming work. Commissioning can take up to two years and requires careful tuning for up to one year afterward as production commences. Changes to the system are expensive as they frequently require interrupting production to implement and test. Robot systems integrate with other factory automation systems to enable just-in-time production and support new levels of economically-viable bespoke manufacturing. Once programmed, a well-designed robotised manufacturing line can switch between creating different models and variants as demand dictates.

Historically, robots are designed and programmed for relatively static environments. Anything unaccounted for in the robot's configuration is essentially invisible, with only minimal feedback such as joint torque, being a guide. These primitive sensory capabilities in most cases necessitate running robots in 'work cells', free from people and other interferences. Once programmed, it is expected that the work environment and artefacts the robot interacts with remain within a very narrow range of variance. Thus the robots are isolated in a physical as well as sensorial sense, little different from any number of dangerous, automated factory machines.

Work environments where powerful industrial robots and humans work together in a cooperative fashion has manifold difficulties. Areas safe for people outside of the robot's working area need to be demarcated and are usually reinforced with physical or sensor-based barriers. Means to interact with or control the robot are typically impoverished, such as pressing a button to activate a task, or entirely non-existent, with the robot responding according to the automation system. If people need to work in close proximity or within the work area of a running robot, it needs to operate at a slow speed so that the risk of physical harm is reduced. Because of these limitations, cooperative working is often restricted through a turn-taking protocol, with paramount risk lying in the transition between turns. For example, a human will perform some work, hand over to the robot to perform some work and so on. In this depiction, we see only glimpses of rich synergy between man and robot, where the natural and unique capabilities of each are fully leveraged.

As a result of the aforementioned shortcomings, along with limitations in tooling, the robot's potential as a versatile factory automation aid is not yet fully realised: it cannot be re-tasked easily and meshes poorly with the rich, dynamic world outside of its work area. In turn, this restricts which environments robots are deployed in and the kind of work they are used for. The cost-benefit ratio for today's robots precludes widespread use by small and medium enterprises, even though the unit price of a robot itself is not prohibitive.

Now that acceptable levels of accuracy, speed, repeatability and dexterity are found in commercially-

---

Manuscript received February 28, 2010. This work was conducted within a collaborative Statoil and ABB R&D project, with additional assistance of the Norwegian Research Council.

Author is with the ABB Strategic R&D for Oil, Gas and Petrochemicals, Oslo, 0553 Norway (phone: +47 22 87 20 00; fax: +47 22 87 49 73; e-mail: clint.heyer@no.abb.com).

available robot systems, additional focus has been placed on human-robot interaction, for example by simplifying programming [1] and reducing harm to people in collisions [2]. Advances in machine learning - and computer vision in particular – have enabled entirely new applications which previously only humans could do, such as pick and place [3] and quality control [4]. Importantly, these techniques are being employed to support a greater degree of adaptive automation.

These approaches have tended to be based on what Brooks [5] terms the ‘symbol system hypothesis’: that the world’s entities can be modelled as symbols and action takes place with respect to symbols as a proxy for the world itself. For example, an industrial robot is configured to have a sense of world coordinates and tool characteristics, and it operates with the world and tool with respect to this model. For robots in a work cell that remain in a fixed location and only reorientate joints, this approach works well, and modern robots are able to perform highly precise positioning with a high degree of repeatability. Difficulties emerge however, when translations between individual robot’s symbolic world representations are required, for example, robot *x* passing an object to robot *y* in a dynamic fashion. Brooks instead proposes a situated approach, based on the ‘physical grounding hypothesis’: that action should take place with respect to direct perception of the world [5]. Generally speaking, this philosophy rejects a dependence on *a priori* modelling, after all, ‘the world is its own best model. It is always up to date. It always contains every detail there is to be known. The trick is to sense it appropriately and often enough’ [5].

These core challenges for industrial robotics are salient for application beyond their common deployment in relatively static factories where they operate, pre-programmed, in large series. Robotics is a broad field, and not all robots - nor all robots used in industry - share the same characteristics as those I broadly described as belonging to ‘industrial robots’. For example, mobile delivery robots are used in factories to shuttle materials, and modern versions designed to function in dynamic environments and are able prevent collision and in some cases proactively route around obstacles. Recent years has seen the introduction of affordable consumer service and entertainment robots, such as the iRobot Roomba and Ugobe Pleo. Designed with a physical grounding philosophy, they are able to successfully negotiate dynamic, haphazard environments.

The next section describes future application areas for robotics in the oil and gas industry and the remainder of the paper examines issues relating to human-robot interaction in relation to this use context and the background hitherto discussed.

II. ROBOTS IN THE OIL AND GAS INDUSTRY

The oil and gas industry typically has a high level of automation in terms of both physical manipulation, such as automated valves and also logical manipulation, such as controlling and managing the process. At an onshore plant, operators monitor and run the process (in conjunction with the automation system) from their central control room, often located some kilometres away from the plant. Field operators are required to perform inspections and maintain equipment, and larger teams carry out repairs and upgrades. In many oil and gas producing regions, workers are exposed to extreme climate (Figure 1), sometimes necessitating working with additional cumbersome protective equipment because of the high levels of hydrogen sulphide contained in the hydrocarbons.

Figure 1. A typical gas refinery can cover a large area in a mixture of outdoor and indoor environments.

Offshore rigs have further logistical issues. It is highly expensive to have people working on the rig, as they must be housed and protected, and in the case of emergency, it must be possible to evacuate personnel quickly. As oil and gas exploration pushes into more inhospitable and remote regions, these difficulties become serious obstacles to the financial viability of an installation.

It is clear then, that there are benefits if robots can perform common field operator tasks in hazardous and unpleasant environments. In the short term, robots can be installed at existing facilities without necessitating systematic change or extensive retrofitting. These can carry out key tasks which have been identified as high risk or high cost. In the longer term, oil and gas companies are planning for entirely unmanned facilities, designed from the beginning to be maintained by robots. Robots are already utilised in the oil and gas industry, for example unmanned underwater robots are often used to visually inspect subsea structures, such as seabed wellheads. The use context presents clear challenges for the design of robotics systems able to operate safely and effectively in explosive, environmentally-sensitive, harsh environments.

Two general scenarios for robots in the oil and gas industry present themselves. The first, teleinspection, is concerned with using a mobile robot to perform inspection of a plant, for example looking for faults that may not be evident to other instrumentation, or performing sample-taking. Rather than permanently installing expensive instrumentation everywhere required, a robot can move instrumentation to where it is required. The second scenario, teleoperation, is concerned with using a mobile robot to perform maintenance, manipulations and repairs. Both of these scenarios could take place either autonomously or manually, under control of a human operator. Robots' versatility and mobility offer better opportunity to address ad-hoc, unexpected needs which may arise while the facility is in production.

III. COOPERATING WITH ROBOTS

Trust and accountability are important considerations for cooperation. Current automated equipment like valves have sensors to determine the outcome of a requested action, and several may be installed in order to improve dependability. If a control room operator tasks a robot with cleaning a particular valve, how is the operator reassured that the task was completed properly? Will an operator have to check up on a robot's work through a video camera, or will the robot be able to reliably judge this for itself? Where does responsibility lie in ensuring work is carried out and completed safely and correctly?

Although people are receptive toward working with robots, it is preferred to work alongside a teleoperated robot rather than an autonomous one [6], highlighting the lack of trust in autonomy. The physical form and behaviour of the robot is important for how it is perceived and should be appropriate for the task [7]. Non-humanoid forms can be perceived as having better personality and friendlier than humanoids, possibly because they are viewed more as machines than as independent actors [8]. People divest less task responsibility when working with non-humanoid robots, and take greater care to ensure tasks are complete [9].

In the oil and gas industry, and particularly for short term uses of robots in existing, manned facilities, it is still an open question as to ideal relationship between human and robot. Operating autonomously carrying out periodic maintenance, the robot could be seen as another element in the tightly-integrated plant automation system. Robots could also be used in a much more directly cooperative fashion in the plant, for example helping people move materials, hold heavy objects, perform sample testing and other mundane tasks. In this scenario, is the robot another tool to ease the burden of physical labour and enhance capabilities, like an electric drill, or does it play the role of collaborative workmate?

Each approach has vastly different demands in terms of interaction design. Tool-oriented use of robots has been investigated in microsurgery, where it is possible for robots to make finer, smoother and more controlled movements than a human hand. Human surgeons can move a proxy tool, which the robot system senses the movement of, analyses, and translates to movement of a robot which performs the actual contact with the patient [10,11]. In the robot-as-tool approach, autonomy is low, and the human should have the potential to act *through* the robot to accomplish their work in a natural fashion. As a collaborative workmate, there are higher expectations for autonomy, for the robot to proffer proactive assistance and to helpfully participate in work activities.

IV. AUTONOMY & ROLES

If robots are to replace field operators, or subsume some of a field operator's tasks, what is the relationship of the robot to the control room operators, shift leaders and other parts of the organisation? Today, control room operators will often request field operators to visit a particular instrument or machine in the field, for example to investigate a problem or to clarify an instrumentation reading. Field operators travel to the plant, find the item and report back via radio. In a future unmanned scenario, a 'field' operator might receive the instruction as before, but this time use a robot to remotely move around the plant and take readings. The operator would analyse readings and report back to the control room operator as is done today. In this scenario, the control room operator is relatively unaware of the robot system, and as before, lays her trust with the judgement and expertise of the field operator and there are few changes to her workflow and practices.

Another alternative is that the control room operator herself commands a robot to investigate an issue, and receives back an automated analysis when complete. This implies a different role for the control room operator, as she must now also command or control a robot as well as performing meta-analysis of the machine-generated analysis. Preliminary ethnographic studies of the oil and gas workplace describe a complex environment which might severely hamper the viability of such automation [12]. Returning to the issue of trust and accountability, if the control room operator cannot depend on the robot to perform an inspection task reliably and accurately, lower levels of automation will be required.

Today, when field operators perform routine inspection rounds of the plant, they keep watch for particular problems (such as wax accumulation) but also for problems they *do not know* they are looking for. Over many repeated inspections, operators gain a situational awareness of what is expected and what is not, and use this awareness across a wide range of activities in the workplace. It might be possible that suitably advanced pattern recognition techniques can be developed to discern all the cues human operators commonly use today. At risk, however, is the rich situational awareness, the sense of 'knowing' the plant. As Endersley and Kaber identify, recovery from errors or shortcomings in an automation system is made more problematic when humans are out of the loop [13].

An adaptive, variable, approach to automation has been suggested as a way to trade off the various benefits and costs associated with automation and manual control, and importantly, keep people as active participants in the robotics system [14]. A fully manual system allows exact control to be exerted, however is labour intensive and may not result in efficient use of robot assets. More sophisticated interfaces and autonomous assistance can further improve efficiency. A fully automated system could take better advantage of robots, however limitations in high-level planning and task execution could require frequent human intervention. Human guidance of robots' tasks and goals allows some of these shortcomings to be addressed [15,16], and shields people from low-level concerns such as joint orientation. Acceptable levels of automation are also necessary to overcome issues with communications latency [17] and controlling multiple robots [18].

The control of several robots also poses critical questions. Are human operators manipulating robots on a one-to-one ratio, shifting focus between them as necessary, or are they managed as a team? Will human operators collaborate together through robot resources? The oil and gas industry, like other workplaces, has a roughly hierarchical structure which mostly hides lower tiers from those above. For example, process engineers generally interact with control room operators, who in turn interact mostly with field operators, who in turn mostly interact with maintenance workers and the process equipment itself. Information and status flows between the various organisational levels, often mediated through informational artefacts such as work permits. At what level is a robot, or team of robots located? In terms of sharing robotic resources, the industry already has existing norms and technology for gaining and releasing exclusive control of remote equipment, managed through the distributed control system. Currently, workers are not spatially tracked as they move around the facility, with radio communication providing enough awareness for the shift team to have a sense of where everyone is. Mobile robots will not participate in this radio communication and thus there is also a need to examine how awareness of their location and activity can be effectively diffused throughout the shift team.

V. REPRESENTATION

How robot resources are represented to a user will largely depend on the level of autonomy the user has engaged. The closer the user is on the spectrum of autonomy toward manual control, the greater emphasis and consideration is required for the depiction of the robots under control. There is a possibility to 'abstract away' the robot system, to make it invisible to the user. Unless the autonomy of the system is sufficiently advanced to manage with all eventualities of a physical robot operating in the real, volatile world, this approach has its limitations. Hiding the robot means that it is only visible when something is wrong: for example a collision or 'seizure' induced by poor joint and path planning. Not only does this reduce the awareness of the issues (how the problem occurred), but also limits the ability for the human operators to be able to apply their experience and skills and avoid the problems before they occur.

Early teleoperation interfaces used multiple 2D views, each with a different representation, for example one showing video from a front-facing camera, one showing video from a rear-facing camera, another showing an instrument readings and so on. Multiple camera views are useful for situational awareness, particularly if the video includes some grounding, landmark features such as the body of the robot [19]. 2D views are particularly useful for precise spatial navigation and reckoning, such as to judge relative positioning while 3D views are more useful for rough navigation in 3D space and getting a sense of 3D formations [20]. There is a large amount of cognitive load for users to merge views and perceive a single state [21,22], a problem made even more difficult when controlling multiple robots. Computing merged views with combined video, a representation of the robot, status information and 3D geometry in a single display is considered an effective option to reduce cognitive load yet still maintain benefits of the different representation techniques [23,24].

In environments with sparse or absent sensing, there is a greater reliance on the robot's on-board capabilities to provide situational awareness for the remote operator. The narrow field of view afforded by traditional approaches has been characterised as the 'keyhole' effect [25], with events and obstacles outside of this field easily missed.

VI. INTERACTION

Beyond screen-based teleoperation interfaces already discussed, there are other input modalities which might offer simpler or more natural interaction with co-located or distant robots. Speech has been examined for service robots [26], but there are still open questions regarding its effectiveness [27]. Multi-modal interfaces can be utilised to take advantage of the respective qualities of each composite modality [28,29]. Richer interaction will enable robots to be controlled with fluidity and less tedious manual operation.

Depending on the system design, there may be two distinct phases of interaction with the robot, for example a programming or teaching phase, and then an execution phase, where previously programmed actions are carried out, or the user performs direct manipulations. To take advantage of a robot's multipurpose nature, it should be possible for a field operator to 'program' it to perform a task, on an ad-hoc basis, which can then be repeated continuously, periodically or on demand. For example, occasional gas leaks may be occurring at an export compressor, so the operator could program the robot to use a gas detector to periodically map out the compressor room. After some time of the robot performing this task, a map could be built to identify the location of the leak. In another case, perhaps a fault has been found in several instrument housings, so the maintenance director would like to do an inspection of all housings. A field operator could program the robot to identify instrument housings and look for the fault. As not all needs for robots will be known *a priori*, and manual direct manipulation is time consuming, end-user programmability would be a useful and challenging agenda for interaction design research. An example of an approach to simple end-user robot programming is ‘programming by demonstration’, in which a robot system observes and repeats human activity [30].

Gesture is an embodied form of interaction which people naturally use in social communication. Gesture has been used, detected through augmented gloves or computer vision, to control remote and co-located robots [31,32,33]. Rather than exercising fine direct control, it is suggested that gesture would be particularly useful for high-level command of robot activity [31]. One example of gesture interaction is a system which allows people to point, with their finger, at an object they wish to pick up, and then point at a location for the object to be placed [34]. For interaction with co-located robots, the advantage of this approach is it allows people to express intent with reference to the actual environment, rather than a symbolic representation thereof.

When controlling a robot, it may not be clear to the user as to why their request could not be carried out. For example, when manipulating an industrial robot, it may not be visually obvious that a joint cannot rotate any further, or a singularity is preventing movement. Similarly with a remote robot, it may not be obvious from the on-screen representation that an obstacle is near, and that driving any closer will cause a collision. Various forms of alerting can be used to notify users of these conditions, including haptics. Haptic feedback can provide physical ‘force feedback’ to an user, for example through vibration, or physically constraining movement of a manipulator, both of which are useful [35,36,37].

VII. CONCLUSIONS

Trends in the oil and gas industry suggest a growing need for enhanced robotic automation in order to conduct operations in regions of the world difficult for humans to work in, as well as to improve the safety and efficiency of workers in existing facilities. Today’s industrial robots have a long-established record for providing reliable, accurate and efficient service in the manufacturing industry. These qualities would also appear to be of benefit for the oil and gas industry and its automation needs. In this paper, several issues with the traditional approach to industrial robotics have been discussed, primarily, the impoverished human-robot interaction means for co-located robots, the dependency on modelled environments and limitations on ad-hoc re-tasking.

In considering the use of industrial robots in the oil and gas industry, several open questions and issues exist. The oil and gas physical environment is exposed to variable, often severe climate, and toxic and explosive materials are present. While new developments might plan for robot deployments, with special consideration for how robots will move around the process and interact with it, robots are also of benefit in existing infrastructure, where there is already large investment. Robots can find application in two broad area: teleinspection and teleoperation. Teleinspection will allow remote operators to be able to perform inspection and sample taking, while teleoperation will permit maintenance and repairs to be carried out with robotic assistance. Together, they can enable operation in areas too hazardous for humans to work in. The degree of automation for these activities will depend on the task, but be moderated by the realistic capabilities of automation. Too little autonomy, and there will be less focus on the task-at-hand. Too much autonomy, and humans will lose situational awareness. How robots fit into existing organisational structures, and how they are accountable to the organisation in terms of safe and reliable operation is yet to be determined. Interaction with robots can take place in a richer more fluid manner than is possible today, for example by leveraging alternative modalities. Composite displays of multi-dimensional information can be used to aid in manipulation and command of robots as well as support remote situational awareness. As this is a new application area, many of these questions cannot presently be satisfactorily resolved, although findings from the use of robots in space, military and search and rescue contexts is of import.

REFERENCES

[1] J. Tatsuno, S. Matsuyama, Y. Kokibo, K. Kawabata, and H. Kobayashi, "Human friendly teaching for industrial robots," in *Workshop on Robot and Human Communication*, 1996, pp. 549-550.

[2] S. Haddadin, A. Albu-Schäffer, A. De Luca, and G. Hirzinger, "Collision Detection and Reaction: A Contribution to Safe Physical Human-Robot Interaction," in *Proc. of Intelligent Robots and Systems (IROS'08)*, Nice, France, 2008, pp. 3356-3363.

[3] M Rygol, S. Pollard, and C. Brown, "Multiprocessor 3D vision system for pick and place," *Image and Vision Computing*, vol. 9, no. 1, pp. 33-38, 1991.

[4] D. Vernon, *Machine Vision: Automated Visual Inspection and Robot Vision*. Englewood Cliffs, NJ, USA: Prentice Hall, 1991.

[5] R. A. Brooks, "Elephants Don't Play Chess," *Robotics and Autonomous Systems*, vol. 6, pp. 3-15, 1990.

[6] A. Weiss, D. Wurhofer, M. Lankes, and M. Tscheligi, "Autonomous vs. Tele-operated: How people perceive human-robot collaboration with HRP-2," in *Proc. of Human-Robot Interaction (HRI'09)*, 2009, pp. 257-258.

[7] J. Goetz, S. Kielser, and A. Powers, "Matching robot appearance and behavior to tasks to improve human-robot cooperation," in *Proc. of Workshop on Robot and Human Interactive Communication (RO-MAN 2003)*, 2003.

[8] V. Groom, L. Takayama, P. Ochi, and C. Nass, "I am my robot: the impact of robot-building and robot form on operators," in *Proc. of Human-Robot Interaction (HRI'09)*, 2009, pp. 31-36.

[9] P. J. Hinds, T. L. Roberts, and H. Jones, "Whose job is it anyway? a study of human-robot interaction in a collaborative task," *Human Computer Interaction*, vol. 19, no. 1, pp. 151-181, 2004.

[10] S. Charles et al., "Dexterity-enhanced telerobitic microsurgery," in *Proc. of Int'l Conf. on Advanced Robotics (ICAR'97)*, 1997, pp. 5-10.

[11] R. Kumar, G. D. Hager, A. Barnes, P. Jensen, and R. H. Taylor, "An Augmentation System for Fine Manipulation," in *Conf. on Medical Image Computing and Computer-Assisted Intervention (MICCAI 2000)*, 2000, pp. 956-965.

[12] C. Heyer, "High-Octane Work: The oil and gas workplace," in *Proc. of European Computer-Supported Cooperative Work (ECSCW'09)*, 2009, pp. 363-383.

[13] M. R. Endersley and D. B. Kaber, "Levels of Automation: Effects on performance, situation awareness and workload in a dynamic control task," *Ergonomics*, vol. 42, no. 3, pp. 462-492, 1999.

[14] M. A. Goodrich, T. W. McLain, J. D. Anderson, J. Sun, and J. W. Crandall, "Managing Autonomy in Robot Teams: Observations from Four Experiments," in *Proc. of Human-Robot Interaction (HRI'07)*, 2007, pp. 25-32.

[15] D. J. Bruemmer et al., "Shared Understanding for Collaborative Control," *Trans. on Systems, Man and Cybernetics*, vol. 35, no. 4, pp. 494-504, July 2005.

[16] D. A. Few, D. J. Bruemmer, and M. C. Walton, "Dynamic Leadership for Human-Robot Teams," in *Proc. of Human-Robot Interaction (HRI'06)*, 2006, pp. 333-334.

[17] J. P. Luck, P. L. McDermott, L. Allender, and D. C. Russell, "An Investigation of Real World Control of Robotic Assets Under Communication Latency," in *Proc. of Human-Robot Interaction (HRI'06)*, 2006, pp. 202-209.

[18] J. Wang and M. Lewis, "Human Control for Cooperating Robot Teams," in *Proc. of Human-Robot Interaction (HRI'07)*, 2007, pp. 9-16.

[19] B. Keyes, R. Casey, H. A Yanco, B. A. Maxwell, and Y. Georgiev, "Camera placement and multi-camera fusion for remote robot operation," in *Proc. of Workshop on Safety, Security and Rescue Robotics*, Gaithersburg, MD, USA, 2006.

[20] C. M. Humphrey and J. A. Adams, "Compass visualizations for human-robotic interaction," in *Proc. of Human-Robot Interaction (HRI'08)*, 2008, pp. 49-56.

[21] B. P. De Jong, E. Colgate, and M. Peshkin, "Improving Teleoperation: Reducing Mental Rotations and Translations ," in *Proc. of Robotics and Automation*, 2004, pp. 3708-3714.

[22] H. A. Yanco and J. L. Drury, "Where Am I? Acquring Situational Awareness Using a Remote Robot Platform," in *Proc. of Systems, Man, and Cybernetics*, 2004, pp. 2835-2840.

[23] C. W. Nielsen, M. A. Goodrich, and R. W. Ricks, "Ecological Interfaces for Improving Mobile Robot Teleoperation ," *Trans. on Robotics*, vol. 23, no. 5, pp. 927-941, October 2007.

[24] F. Ferland, F. Pomerleau, C. Le Dinh, and F. Michaud, "Egocentric and exocentric teleoperation interface using real-time, 3D video projection," in *Proc. of Human-Robot Interaction (HR'09)*, 2009, pp. 37-44.

[25] M. Voshell and D. Woods, "Breaking the Keyhole in Human-Robot Coordination: Method and Evaluation," in *Proc. of the Human Factors and Ergonomics Society 49th Annual Meeting*, 2005, pp. 442-446.

[26] S. Lauria, G. Bugmann, T. Kyriacou, and E Klein, "Mobile Robot Programming Using Natural Language," *Robotics and Autonomous Systems*, vol. 38, no. 3-4, pp. 171-181, 2002.

[27] S. Thrun, "Toward a framework for human-robot interaction," *Human-Computer Interaction*, vol. 19, no. 1, pp. 9-24, June 2004.

[28] R. Stiefelhagen et al., "Natural human-robot interaction using speech, head pose and gestures," in *Proc. of Intelligent Robots and Systems (IROS'04)*, 2004.

[29] D. Perzanowski, A. C. Schultz, W. Adams, E. Marsh, and M. Bugajska, "Building a Multimodal Human-Robot Interface," *Intelligent Systems*, vol. 16, no. 1, pp. 16-21, January 2001.

[30] M. Ehrenmann, O. Rogalla, R. Zölnner, and R. Dillmann, "Teaching Service Robots Complex Tasks: Programming By Demonstration For Workshop And Household Environments," in *Field and Service Robots (FSR)*, 2001, pp. 397-402.

[31] S. Iba, M. Vandeweghe, C. Paredis, and P. K. Kholsa, "An Architecture for Gesture-Based Control of Mobile robots," in *Proc. of Intelligent Robots and Systems (IROS'99)*, 1999, pp. 851-857.

[32] S. Waldherr, R. Romer, and S. Thrun, "A Gesture Based Interface for Human-Robot Interaction," *Autonomous Robots*, vol. 9, no. 2, pp. 151-173, September 2000.

[33] M. M. Loper, N. P. Koenig, S. H. Chernova, C. V. Jones, and O. C. Jenkins, "Mobile human-robot teaming with environmental tolerance," in *Proc. of Human-Robot Interaction (HRI'09)*, 2009, pp. 157-164.

[34] R. Cipolla and N. J. Hollinghurst, "Human-robot interface by pointing with uncalibrated stereo vision," *Image and Vision Computing*, vol. 14, no. 3, pp. 171-178, April 1996.

[35] D. P. Barnes and M. S. Counsell, "Haptic communication for remote mobile manipulator robot operations," in *Proc. American Nuclear Society's Topical Meeting on Robotics & Remote Systems*, 1999.

[36] N. Turro and O. Khatib, "Haptically Augmented Teleoperation," in *Int'l. Symposium on Experimental Robotics (ISER2000)*, 2000, pp. 1-10.

[37] S. Lee, G. S. Sukhatme, G. J Kim, and C. Park, "Haptic Control of a Mobile Robot: A User Study," *Presence*, vol. 14, no. 3, pp. 345-365, 2005.

[38] L. Takayama, W. l Ju, and C. Nass, "Beyond dirty, dangerous and dull: what everyday people think robots should do," in *Proc. of Human-Robot Interaction (HRI'08)*, 2008, pp. 25-32.

[39] G. Podnar et al., "Human telesupervision of a fleet of autonomous robots for safe and efficient space exploration.," in *Proc. of Human-Robot Interaction (HRI'06)*, 2006, pp. 325-326.

[40] P. Lapides, E. Sharlin, and M. C. Sousa, "Three Dimensional Tangible User Interface For Controlling A Robotic Team," in *Proc. on Human-Robot Interaction (HRI'08)*, 2008, pp. 343-350.