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# HUMAN-ROBOT INTERACTION: ADVANCED TASK-CENTERED INTERFACES FOR NON-EXPERT USERS

## INTERAKCE ČLOVĚKA S ROBOTEM: POKROČILÁ ÚKOLOVĚ ORIENTOVANÁ ROZHRANÍ PRO NEODBORNÉ UŽIVATELE

PH.D. THESIS EXTENDED ABSTRACT
ROZŠÍŘENÝ ABSTRAKT DISERTAČNÍ PRÁCE

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# ABSTRACT

Recent years brought a growing trend of deploying robots in novel applications where they are not only supposed to co-exist with and work next to humans but to actually closely collaborate with them on shared complex tasks. Capabilities of the robotic systems need to be substantially expanded in order to make the close, rich as well as natural human-robot interaction possible. Indeed, the interaction will not only happen between caged robots and highly specialized experts any more. More and more often, it will interconnect safe and interactive robots with non-expert users with various background. Consequently, the amazingly complex machines, that the current robots are, will become even more complex. This poses further challenges for the design of their user interfaces.

The objective of this thesis is to research and develop solutions for the close interaction between non-expert users and complex robots. The research was done in two different contexts: assistive service and industrial collaborative robots. Although these two domains have diverse requirements, related concepts could be used when designing the human-robot interaction. To cope with limitations of the current approaches, a novel method for task-centered interaction has been proposed. The most important aspects of the method are the utilization of mixed reality and robot-integrated capabilities, communication of the robot's inner state, context sensitivity, and usage of task-appropriate modalities. For each of the two mentioned domains, a user interface was designed and implemented. Both interfaces were successfully evaluated with non-expert users, who were able to carry out non-trivial tasks in cooperation with a robot. The reported evaluation provides an evidence that the realized method significantly improves the close human-robot interaction, which had not been entirely possible with previous approaches. The method's key characteristics provide guidelines for new designs of next user interfaces in the collaborative robotics.

# KEYWORDS

Human-robot interaction; teleoperation; remote manipulation; colllaborative robots; simplified programming.

# CONTENTS

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# 1

# MOTIVATION AND BACKGROUND

> *An automated machine that does just one thing is not a robot. It is simply automation. A robot should have the capability of handling a range of jobs at a factory.*
>
> — Joseph Engelberger

A close, face to "face" human-robot interaction has been so far more topic of research or science-fiction than something that actually happens in everyday life (with exception of robotic vacuum maintenance). Apparently, this will change sooner or later as robots for various applications are getting more affordable and human labor tends to be more expensive. First, a close interaction between humans and robots will become more frequent in industry, where caged robots are being replaced by collaborative ones. As the robots will move out of the cages, they will work alongside human workers. Then, trend towards humans and robots closely collaborating on the same task could be expected in order to increase productivity. To enable such close collaboration and maintain safety, a rich human-robot interaction will be inevitable. At the same time, service robots will more and more often come to contact with people in hospitals, institutional care facilities and prospectively also in private households. What have industrial robots in common with service robots? There must be some interface allowing human users interact with them: to check their state, give them goals, visualize robot intentions, etc. In general, in both contexts it has to be assumed that the users are general public, majority of them will not be roboticians or programmers and the future interface design has to respect this.

## 1.1 ORGANIZATION OF THE WORK

The extended abstract of the thesis (which is in the form of a collection of articles) is organized as follows. This chapter provides definition of the basic framework of the thesis as well as motivation and justification for the conducted research. Chapter 2 formulates the thesis statement, the related objectives and presents the achieved contributions. A general state of the art overview is given within Chapter 3. Despite overview of the academic solutions, also commercially available ones are included. A more specific overviews of (academic) state of the art could be found within the respective sections of the papers included within the thesis. Based on the current state of the art, a novel method for human-robot task-centered interaction is proposed in Chapter 4. Chapter 5 concludes this work.

## 1.2 SCOPE OF THE THESIS

The scope of this work follows the two main projects in which I was involved during my Ph.D. studies.

Figure 1.1: Elderly person being served by the SRS robot within user tests in a laboratory imitating home environment (credit: http://srs-project.eu/milan_test_may)

The first project was Multi-Role Shadow Robotic System for Independent Living (SRS)[1]. It was focused on development of user interfaces for semi-autonomous personal care robot, helping elderly people to life independently at home as long as possible (see Figure 1.1). Specifically, I worked on user interface for teleoperation of the robot in cases, where it could not handle particular action autonomously.

The second project is Collaborative robot 2.0: cognition of the work environment, augmented reality-based user interface, simple deployment and reconfiguration[2]. Goal of the project is to come-up with novel solutions for collaborative robots, to simplify their deployment in small and medium-sized enterprises (SME). I'm research leader of this project and my main responsibility is a design, implementation and testing of a projected user interface (see Figure 1.2).

In either case, methodologies originating from human-computer interaction (HCI) were used to design and evaluate interfaces. Moreover, both cases are linked by focus on non-expert users, where interaction was designed in order to take as much advantage as possible from robot-integrated capabilities as e.g. sensing of the environment and motion planning.

The following sections provide a brief overview of the past and present directions in the field of human-robot interaction (HRI) research (Section 1.3), introduction into specifics of personal service robots (Section 1.4), collaborative industrial robots (Section 1.5) and the chapter is closed by a summary with respect to the scope of this thesis (Section 1.6). The both Sections 1.4 and 1.5 also provide overview of the past research projects in the respective area of interest. The purpose of this overview is to

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[1] EU-7FP-IST - Seventh Research Framework Programme, 7E12056, 247772, 2011-2013, http://srs-project.eu.

[2] Funded by Technology Agency of the Czech Republic, project code TJ01000352, duration from 2017-09-01 to 2019-08-31.

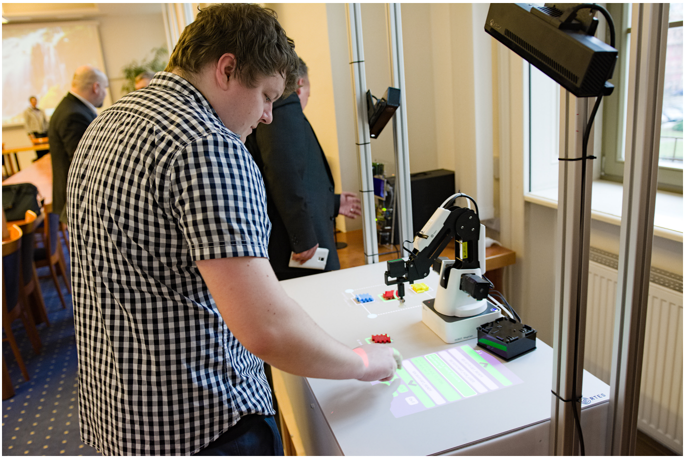

Figure 1.2: The user programs a table-top robot to perform a pick and place task.

provide an insight into the broader context of recent activities within the field and justification of the selected research topics.

## 1.3 HUMAN-ROBOT INTERACTION

The HRI is an interdisciplinary research domain originating from human-machine interaction (HMI) and HCI fields. According to the definition (based on usability research) from [19] it is *"a field of study dedicated to understanding, designing, and evaluating robotic systems for use by or with humans"*, while its problem is *"to understand and shape the interactions between one or more humans and one or more robots"*. Broader definition was stated in [12]: *"HRI is the science of studying people's behaviour and attitudes towards robots in relationship to the physical, technological and interactive features of the robots, with the goal to develop robots that facilitate the emergence of human-robot interactions that are at the same time efficient (according to the original requirements of their envisaged area of use), but are also acceptable to people, and meet the social and emotional needs of their individual users as well as respecting human values"*. As it turns out from definitions, inherent part of HRI is design of robots. Naturally, robots have to more or less (based on their application) interact with humans so, there has to be some user interface to mediating this interaction.

In this thesis, the scope will be limited to the design of robot interfaces, in particular for personal service robots and for collaborative industrial robots. Those types of robots are usually incredibly complex machines. Machines based on sophisticated hardware and with continuously improving and expanding capabilities. Although robots does not posses general artificial intelligence (AI) yet, anyway it might be highly difficult to understand their inner state, to predict their actions, to understand what and how they perceive [66]. Communicating robot's inner state to the user could be seen as one of the main challenges in design of user interface (UI). As robots are usually not working all the time in a fully stand-alone mode, there is also need to direct their activity, in another words, to set them goals or to coordinate the joint task between the human and the robot.

Previously, a lot of research was focused on teleoperation of robots as at the time, use cases where direct (face to face) or close HRI could occur were highly limited as service robots were non existent and in the industry, robots were strictly separated from humans[3]. With emergence of safe industrial robots (e.g. UR5 by Universal Robots in 2008) as well as research service robots (e.g. PR2 from Willow Garage in 2010), more effort was put into research of the close HRI.

For an interface to be functional (and bidirectional), there has to be at least on input and one output modality. Traditionally, the output modality used to be mainly a computer screen. Within the context of teleoperated robots, an ecological approach to UI design gained significant popularity [48] with its main benefit of improved situational awareness over "traditional" (2D video) interfaces. Input modalities tend to be mouse, keyboard or joystick. Recently, many less traditional modalities were investigated as various controllers (3D mouse, inertial measurement unit (IMU)-based devices), stereoscopic displays, virtual reality (VR), etc. To enable closer interaction within the context of collaborative robots, it is inevitable for the robot to perceive its environment and especially its human partner: his/her position, activity, or intentions.

## 1.4 PERSONAL SERVICE ROBOTS

The term service robot is according to the International Organization for Standardization (ISO) standard 13586 defined as *"robot that performs useful tasks for humans or equipment excluding industrial automation applications"* [26]. Current spread of service robots includes: logistics, care, telepresence, domestic usage, security, agriculture, entertainment, etc. Applications of the robots could be divided into the two main categories: professional and personal. This work focuses on the second one, more specifically on personal care robots with navigation and manipulation capabilities. However, there is currently no such robot available on the consumer market[4] although the ISO standard defining safety requirements of such robots is available since 2014 [25][5]. There exist several platforms for research and developmen.

In the near future, adoption of the service robots is expected to rise – according to the International Federation of Robotics (IFR), sales in the segment are going to rise 20-25 % in the period 2018-2020[6]. It is also estimated that by the end of 2019, up to 31 million domestic household and 11 million entertainment and leisure robots will be deployed[7]. Those forecasts justify importance of research in the field of close HRI.

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[3] For good reasons, see i.e. `https://en.wikipedia.org/wiki/Robert_Williams_(robot_fatality)`

[4] Few so-called companion robots are available as e.g. Paro, or mobile robots without manipulation capabilities as e.g. KOMPAÏ.

[5] It concerns: physical assistant robots, mobile servant robots, and person carrier robots.

[6] https://ifr.org/ifr-press-releases/news/why-service-robots-are-booming-worldwide

[7] https://ifr.org/ifr-press-releases/news/31-million-robots-helping-in-households-worldwide-by-2019

## 1.5 COLLABORATIVE INDUSTRIAL ROBOTS

The term industrial robot is according to [26] defined as *automatically controlled, reprogrammable, multipurpose manipulator, programmable in three or more axes, which can be either fixed in place or mobile for use in industrial automation applications* and collaborative robot (often also referred to as cobot) as *robot designed for direct interaction with a human*. The Intelligent Assist Device (IAD)[8] may be seen as an alternative to cobot; however, it does not fulfill the first one definition.

Traditionally, in mass production the desired state was a 100% automation in order to maximize benefits resulting from the economics of scale. Nowadays, mass production evolves into mass customization which is an inherent part of the Industry 4.0 paradigm and imposes significant improvement of flexibility. On the other hand, at SME companies, flexibility of the production was always important. At the same time, with rising availability of (collaborative) robots, they are deployed at SMEs more and more often [24]. In order to allow a higher flexibility and improve productivity, there exists a trend towards:

1. Removing the strict spatial and temporal separation of human workers and robots.
2. Hybrid assembly cells, where human and robot work in parallel on the joint task.

Both trends are possible due to collaborative robots, which are designed to be safe to work alongside humans. However, a cell fitted with a collaborative robot is not automatically fully safe and risk assessment for the particular application has to be performed to comply with ISO/TS 15066:2016. The most common use is for tasks as packaging, palletizing, automatic (bin) picking, quality control, assembly, sorting, sanding, polishing, etc. A vision is often utilized to cope with uncertainty as e.g. slightly variable position of parts. The main advantages over caged/fenced robots are:

- Easier deployment and programming.
- Reduced expenses on safety equipment (sensors, barriers).
- Better utilization of floor space - lower real estate expenses.
- Enabling to form hybrid cells.

Additionally, the hybrid cells where human and robot may work in parallel might be more expensive; however, poses several advantages:

- Increased productivity.
- More uniform quality.
- Lowering risk of health problems by offloading a repetitive or non-ergonomic parts of the task to a robot.

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[8] Gravity compensated manipulator for material handling and assembly operations.

Four types of human-robot collaboration are defined in [16]:

- Safety-rated monitored stop
- Hand guiding
- Speed and separation monitoring
- Power and force limiting

## 1.6 MOTIVATION AND BACKGROUND SUMMARY

So far, actually deployed robots tend to be moreover pre-programmed machines, exactly following the given procedure, with none to low abilities to interact with humans. Within the academic research domain, a lot of effort was made in order to allow more or less natural HRI. However, there still remains unsolved challenges and many of the problems were solved in a rather isolated way. Within the commercial sphere, there seems to be trend of growing importance of interactive features, probably driven by demand for hybrid assembly cells, which are; however, currently still not truly widespread. In a near future, interaction-able robots will likely become reality and later they will become omnipresent. Therefore, it is necessary to develop appropriate interaction methods and derived interfaces for such robots.

# OBJECTIVES AND CONTRIBUTIONS 2

*Research is what I'm doing when I don't know what I'm doing.*
— Wernher von Braun

The area of interest of this thesis and its significance was justified in Chapter 1. In this chapter, the thesis statement is formulated together with related research objectives and overview of the main contributions is given.

The thesis statement was selected as a more appropriate for this work, instead of hypothesis or research question (which is equivalent to hypothesis, just formulated in form of a question) as the research in the field of HRI is largely of a qualitative or at the best of a mixed nature [54, 31]. Because of that, it is problematic to formally prove or disprove a hypothesis commonly used in domains where quantitative research prevails.

## 2.1 THESIS STATEMENT

The thesis statement directing the research efforts within this work is formulated as follows:

**A specifically designed user interface may enable non-expert users to accomplish non-trivial joint tasks with highly complex robots.**

For the purposes of this work, "non-expert user" is a user without specific knowledge of robots, automation, or computer science; however, potentially with domain or task specific knowledge. The robot should be understood as a personal service robot or a collaborative industrial robot. A complex robot, is a robot with at least partial autonomy and basic cognitive abilities. This work aims on an interaction where a user and a robot collaborate on the same task (spatially collocated or displaced), they interact regularly and in a non-trivial way and the interaction preferably happens within the task space. Such interaction is referred to as "close".

## 2.2 RESEARCH OBJECTIVES

In order to gain support for the thesis statement, following objectives were formulated.

### 1. *Define an integrative method for close human-robot interaction.*

As it could be seen from the state of the art overview (see Chapter 3), the existing methods are still somehow limited in various aspects. Promising partial approaches have been published; however, with limitations as e.g. suitability for only trivial tasks or on the other hand, unsuitability for non-expert users. Consequently, there is an opportunity to integrate those partial approaches into a novel method which could serve as a basis for design of next generation user interfaces allowing effective task-centered interaction.

*2. Apply the method within the contexts of interest.*

In order to allow evaluation of the method and demonstrate how it generalizes to different contexts (use cases), more than one user interface based on the method should be implemented. Naturally, specifics of the contexts have to be taken into account. The contexts of interest within this thesis are assistive service robots and collaborative industrial robots.

*3. Investigate if and how underlying autonomy could support human-robot interaction.*

Interacting with a highly complex and eventually fully or partially autonomous robot might be challenging for various reasons: automatically triggered actions of the robot might be confusing (*why the robot did that?*), natural communication cues from human-human communication are missing or are insufficiently supplemented, etc. Interaction becomes even more challenging if it happens remotely, where the user also has to build a mental model of the remote environment and track or estimate its state.

It is hypothesized that the interface enabling user to trigger and parametrize robot autonomous functions would help to keep mental workload low and thus maintain collaboration effective.

*4. Investigate what modalities are appropriate for convenient interaction.*

Input and output modalities are the essence of each interface. The modalities and their usage have to be chosen appropriately according to the robot, the user, the environment and the task at the hand. Inputs has to enable users to influence robot actions and outputs have to communicate robot's current state, task state, problems, etc. Multimodal interaction has to be designed in a way, that it provides a coherent and plausible user experience.

*5. Investigate how the joint task should be presented to make it comprehensive and how to support situation awareness.*

For any team to be effective, the joint task has to be known in the first place and naturally, it has to be understood by all participating members. Moreover, task progress, changes to plan and exceptions has to be tracked. The robot may perform all of this internally as well as human. However, a human short-term memory capacity is limited and high mental load might lead to an increased workload. Thus, the required information should be provided by the interface. On the other hand, overwhelming the user with too much data would be counterproductive. Information has to be shown intelligently, in a context-sensitive manner.

*6. Evaluate the method-based interfaces with non-expert users.*

The method can only be evaluated indirectly, through evaluation of the user interfaces based on it. Although usability or technical issues of the concrete implementation will definitely play role in the evaluation and will affect the results, if the main aim of the interface will be satisfied without major issues, it could be claimed that the objective was fulfilled.

## 2.3 CONTRIBUTIONS

The main contribution of this thesis is the novel method for task-centered interaction (further described in Section 4.1). Moreover, for the purpose of context-specific evaluation of the method and its particular aspects, two fully functional user interfaces based on the method have been developed, enabling non-expert users to:

- teleoperate assistive service robots and
- program industrial robots and collaborate with them.

Both interfaces are based on centering the interaction into the task context and mixed reality: a virtual 3D scene in case of teleoperation and a shared workspace with interactive spatial augmented reality (ISAR) in the case of industrial robot programming. The usage of mixed reality helps to avoid attention switches and to lower mental demands, thus improving efficiency of interaction. Low level control is avoided by using a semi-autonomous robot, with advanced sensing capabilities, able to carry out particular tasks independently. Both approaches sharing the same fundamental principles were evaluated in several user studies with promising results (for overview see Section 4.2).

## 2.4 PUBLICATIONS

The conducted research has been published in several papers, where those where I was the main contributor are included as chapters of the full thesis (with my contribution expressed as a percentage in parentheses):

- *Teleoperating Assistive Robots: A Novel User Interface for Remote Manipulation and Navigation Relying on Semi-Autonomy and Global 3D Environment Mapping* (40 %).
- *Simplified Industrial Robot Programming: Effects of Errors on Multimodal Interaction in WoZ experiment* (40 %).
- *Using Persona, Scenario, and Use Case to Develop a Human-Robot Augmented Reality Collaborative Workspace* (50 %).
- *Interactive Spatial Augmented Reality in Collaborative Robot Programming: User Experience Evaluation* (35 %).

Other relevant publications which I significantly contributed to:

- Design of the human-robot interaction for a semi-autonomous service robot to assist elderly people [39] (10 %).
- Teleoperation of domestic service robots: Effects of global 3d environment maps in the user interface on operators' cognitive and performance metrics [38] (15 %).
- Semi-autonomous domestic service robots: Evaluation of a user interface for remote manipulation and navigation with focus on effects of stereoscopic display [40] (20 %).
- Industrial human-robot interaction: Creating personas for augmented reality supported robot control and teaching [61] (10 %).

I also contributed to the following technical report:

- Deliverable D4. 5.2–Context-aware Virtual 3D Display Final Report [59] (20 %).

# GENERAL STATE OF THE ART 3

## 3.1 RELATED WORK

This chapter provides overview of the recent existing work within the scope of this thesis complementary to the respective sections of the included papers, which are focused more specifically according to the topic of each paper. Sections 3.1.1 to 3.1.3 corresponds to "investigative" objectives 3, 4 and 5 stated in Chapter 2. To the end, Section 3.2 offers a brief overview of current non-academic solutions already available on the market and Section 3.3 provides summary.

### 3.1.1 *Semi-autonomous Robots*

This section particularly focuses on ability of different approaches to cope with (non-expert[1]) user input: if and how robot (semi-)autonomous functions are parameterizable and triggered.

In order to allow robots to function efficiently and safely in a complex and highly unstructured or semi-structured environments as private households and SME, some form of a partial autonomy is often utilized. The partial autonomy in this case means, that the system is able to cope with user inputs and adjusts its function according to them or may be temporarily switched to more or less manual control mode[2]. Various approaches exists as: semi-autonomy, adjustable autonomy, mixed initiative, sliding autonomy, etc. Within these approaches, interfaces are usually specifically designed to minimize cognitive load (a concept associated with working memory in the cognitive load theory) of the users which is achieved by various means. A target user group has to be known and considered to, among others, avoid expertise reversal effect [30] which may occur when an over-simplified user interface (providing too much guidance or abstracted information) is used by individuals with more prior knowledge [28]. Within the context of assistive robots, possible cognitive or physical limitations of the end users has to be taken into account.

An underlying autonomy of the system could assist users to simplify e.g. manipulator control. In [64], a grasp database and motion planning is used to control arm of the assistive robot. The user sets Cartesian coordinates of the end effector and may press button to initiate an autonomous grasp or place sequence. Orientation of the end effector is set automatically according to current mutual position of the effector and an object to be grasped. Another approach, usable for teleoperation over high-latency or unreliable networks, is based on user intent recognition [9]. The system classifies (delayed) user input and according to scene state provides assistance. The user is given freedom to switch system modes (manual, semi-autonomous, autonomous), synchro-

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[1] https://en.oxforddictionaries.com/definition/non-expert

[2] Full manual control is often not applicable as e.g. setting each joint position during teleoperation session of high Degrees of Freedom (DoF) robot would be extremely difficult if not impossible.

nize local visualization with remote actual state or to plan robot motion to fit its state in the local visualization. While previously mentioned systems were limited to one functionality, the system from [20] represents an integrated environment with different tools to support daily living activities of a motor impaired user. Its video-centric web-based interface allow control with a variable level of autonomy: an object may be selected by a user and then grasped autonomously, or a user may set gripper pose and close the gripper manually. The system is also equipped with a task-level planning system to provide cognitive support during complex or long-running tasks and to enable task-relevant undo function. During operation, the interface shows steps of the current task and automatically switches its mode, according to the current step of the task. The user may decide to perform any part of the task manually or has to it if the automatic execution fails.

Another approach (used extensively for rescue robots, for instance during DARPA Robotics Challenge) is based on affordances, defining relationship between a robot and actionable objects in its environment. The interface described in [37] is based on an integrated task execution system and affordances (constituting of 3D model and metadata) for interaction with physical objects. The affordance may be detected automatically, an operator may give a hint to the perception system (e.g. by selecting a region in the image) or fit the affordance fully manually. The operator may preview the robot plan and request or decline its execution. Normally, the task is executed fully autonomously and the operator just supervises its execution. If needed, the operator may switch to a semi-autonomous operation (e.g. by providing a previously mentioned hint to the perception system) or to a low-level teleoperation.

In industrial applications, high-level robot programming based on underlying autonomous functions gain a significant attention. For instance, the mobile manipulator in [50] supports a task-level programming based on a small set of parametrizable skills (derived by the authors from existing worker instructions), where parameters are set either by a user through various modalities or by an automatic task planner. In this approach (and also generally), a skill is composed of primitive robot motions (motion primitives). The skills are object-centered – meaning that program execution depends on cognition and that execution is to some degree robust to changes in the environment. The approach from [56] is also based on a task-level programming; however, the used interface is highly unconventional: specifically designed tangible blocks are used to select objects, to assign a required action as well as to specify order of actions. A robot's program is compiled from used blocks. The advantage of the approach is clear: interaction occurs within the task context and is highly intuitive (requires no learning). On the other hand, suitability for more complex tasks seems questionable, despite recent addition of a projected overlay, providing support during robot programming [57].

Further overview of the related work related to semi-autonomy may be found in the **??**.

### 3.1.2 *Modalities and devices*

Any machine (e.g. a computer, a robot), in order to be usable by humans, must have an interface through which happens interaction between the machine and its user.

The interface has one or more input and output channels. These channels are called modalities, where a single modality could be defined as a mode of communication according to human senses or type of computer input devices [27].

If interaction happens through more modalities, it becomes multimodal. As a human-human communication is inherently multimodal, the multimodal interaction is in general considered as a more natural than the singlemodal interaction. The most often utilized human senses are vision and hearing as they constitute a high bandwidth communication channels. Different input or output modalities could be used simultaneously as it is the case in a human-human interaction or consecutively as it is so far the case in most human-machine interactions. Each modality may be used to communicate different type of information, or more modalities may be used to communicate the same information – in this case, the interface could be considered as redundant [68].

The choice of modalities and their actual usage depends on the particular task, a robot and an end-user group. For personal robots, speech is often utilized although natural language processing is a highly complex problem. In order to cope with associated difficulties, authors of [13] evaluated an approach based on vision and speech recognition supported by a learning algorithm and a set of failover modalities (mobile phone application, external microphones, and a tablet mounted on the robot's chest) to make interaction with a social robot more robust. The results from [58] suggests, that a combination of more simple modalities (color, sound and vibration) may successfully convey emotions (happy, sad, angry, relaxed).

If the task permits, even a robot's body may be used as an interface. For instance, robot's intents may be indicated by its posture [5] or by a specifically designed motion [8]. Also the robot arms may be used for inputting information (see Section 3.1.2.2).

Similarly, a user's posture or motion may be used to communicate information to the robot. For instance, pointing in the household scenarios was shown to have a sufficient accuracy (9.6 cm) for object selection [53]. Gestures might be detected using vision, depth data, by a wearable device as e.g. Myo Armband [51] or by an IMU device such as Wii Remote [3]. However, in real-world applications, gesture-based control might not be robust enough as it has to cope with e.g. spontaneous human motions [52]. Similarly to gestures, gaze could be used to select objects e.g. to command a robot to pick them up [34]. The gaze-based input is of special importance for users with motor impairments and thus limited other possibilities of commanding a robot. Moreover, a user's physiological condition could be measured by a biofeedback sensor allowing a system to adapt dynamically to the user e.g. by estimating workload [23]. Emotional state of the user (anger, happiness) might be estimated using a far infrared camera [7].

The task sensitivity of modality selection could be demonstrated on results from [55] where three modalities (voice, gesture and tablet) were used for two tasks: training of a welding path and correction of the trained path. While the tablet performed best for the path planning (in terms of a self-reported mental workload), a voice control was better for path correction. Moreover, the importance of modality selection rises with the task complexity [62].

Probably the most common form of a human-robot interface is still a Graphical User Interface (GUI) application on a standard computer monitor accompanied by a mouse and a keyboard. Eventually, the visualization within this setup might be stereoscopic to improve depth perception [64, 40]. Various devices could be used in conjunction with the mouse and the keyboard for input as e.g. a joystick or a 3D mouse [64].

Recently, handheld devices with a touch screen gained a significant attention thanks to their portability and ability to realize augmented reality (AR) (more on AR in Section 3.1.2.1). For instance, the system from [50] uses a tablet to create sequence of skills constituting program of an industrial robot. Consequently, other methods as kinesthetic teaching and pointing gestures are used to set parameters of skills, e.g. to select a particular object for "pick object" skill. The touch-based device may be even integrated into the robot itself [13, 5, 15]. The main advantages of the touch input are that it is easy to use and widely known to the general public.

#### 3.1.2.1 *Mixed reality*

The mixed reality could be understood as a display method based on the merging real and virtual environments. More exactly, the mixed reality lies anywhere on the "virtuality continuum", except its extrema (real and virtual environments) [46]. According to such definition, the augmented reality should be considered as a subset of mixed reality; however, in practice, the terms are commonly used interchangeably. In other words, the objective of the mixed reality is to enhance the reality with an artificial content rather than provide a purely virtual immersive environment as it is the case for virtual reality [6]. The augmented reality system is supposed to have three following characteristics [4]:

1. Combines real and virtual.
2. Interactive in real time.
3. Registered in 3D.

A mixed reality platform might be based on a handheld device [45, 60, 35], a head mounted display [22, 65] or a camera-projector solution [10, 11, 17]. When designing the interface, perceptual issues as e.g. a limited field of view, a depth ordering and occlusion introduced by the selected technology and used method has to be taken into account [33]. Despite potential problems, the mixed reality has potential to improve HRI. For instance, it could help to avoid context switches which are normally inevitable when the user has to observe the real environment and the robot as well as the video interface [22]. Another usage could be to convey the robot's intents, especially for appearance-constrained robots [65, 10, 11] not able to convey those by other means.

Nowadays, especially spatial augmented reality (SAR) seems to be a highly promising method enabling users to interact with the robot within the task-context. For instance, its use was investigated to program a mobile welding robot [3] or in a long-term study focused on projecting assembly instructions [17]. In contrast with handheld devices, SAR has following advantages: both hands are free, projection is visible by anyone, no physical load caused by need to hold the device. Although the head mounted display also frees users' hands, there is question of its long-term use suitability (possible health risks) and moreover, contemporary devices are expensive[3] and

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[3] Microsoft HoloLens Commercial Suite $5.000, Meta 2 Augmented Reality Development Kit $1.495, MagicLeap One The Creator Edition $3.000 (expected price).

probably not robust enough for e.g. usage in industrial environments. Moreover, the head mounted displays are either tethered or with limited battery life[4] which might limit its deployment even further.

As the mixed reality is relatively new (both in general as well as in the field of HRI research), there is lack of proven interface patterns, design guidelines and usability evaluation methods. As the technology is not mature, technical problems are also common (lagging interface, bad registration, etc.). All of the previous problems might contribute to sort of contradictory results of some studies. For instance, the study from [35] reports a positive effect of AR; however, the users of the AR needed more support than those using baseline solution. In the long-term study [17], the AR system projecting assembly instructions leaded to reduced learning curve of novice assemblers; however, performance for expert workers decreased. In the study [60], usage of the tablet-based AR leaded to decreased mental demands; however, to increased task completion times.

#### 3.1.2.2 *Physical interaction*

A physical interaction of a user and a robot may refer to an unwanted contact between those two or to an intended contact in cases where the robot (arm) itself is used as an input or output modality. The intentional interaction could happen with the robot itself (if the robot arm could reduce its stiffness) or trough an additional device. Probably the most common examples of using a robot's arm as an input modality are kinesthetic teaching [67] and programming by demonstration [1]. Those methods seem relevant especially for non-expert users. For instance, in the user study [67], participants with no prior experience with industrial robots and with good spatial vision abilities rated physical interaction as easy, comfortable and self-explanatory. On the other hand, participants with prior experience rated the interaction less self-explanatory and reported a higher cognitive load. Another possible approach is to command the robot with relatively simple haptic commands as taping and pushing [18], which could potentially improve user experience and allow to better maintain physical and cognitive engagement with the task. Despite utilizing a robot arm as an input device, the arm could also communicate information to the user – acting as an output modality [8], or it could even act in a bidirectional manner [63]. Robot arms not originally designed for any form of physical interaction could be retrofitted to provide such functionality, e.g. by addition of tactile surface sensors for gesture input [47].

### 3.1.3 *Task presentation and situation awareness*

An explicit communication (usually by visualization) of the task and its current state is usually not needed for trivial tasks (as those quite often used in user experiments). However, for more complex tasks as e.g. assembly of a product or long-running tasks as e.g. a remote manipulation with many required steps, the issue of a suitable task presentation arises. Knowledge of the current task state is related to situation awareness, as well as to safety. For instance, when the user knows which object is the robot

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[4] Microsoft HoloLens has declared battery life of 2-3 hours of active use.

going to manipulate, he or she can avoid touching it and thus avoid potential collision [36]. However, there is a challenge on how to display state of a highly complex system (e.g. a cooperative workcell) in a comprehensive form [14]. There exist several solutions for (collaborative) robot programming [2, 56, 32]; however, only a few of them also provides some task execution monitoring [3, 49, 21, 37] – usually limited to highlighting current step of the program, without any further cues for the human user. Some of the solutions uses elements of within task-space interaction, as e.g. SAR for setting welding points [3] or kinesthetic teaching for setting positions [50]; however, the major amount of interaction still happens on a monitor or a handheld device. In that case, the split attention effect [29] may occur, leading to unnecessary increase of user's cognitive load.

## 3.2 COMMERCIALLY AVAILABLE SOLUTIONS

When considering personal robots available on the market, the existing options are moreover limited to some form of intelligent assistants similar to Amazon Alexa or Google Home (which may be considered as smart speakers), although robotized to some extent. Typically, the functionalities include: natural language processing, facial recognition, notices, controlling smart home appliances, security features, telepresence, sharing or getting information, etc.

For instance, despite aforementioned typical functions, Jibo by the company of the same name has articulated torso and is able of smooth animated motions. In contrast to speaker-like intelligent assistants, the interaction between Jibo and the user may be potentially richer – the robot may express certain information using motion and a touchscreen face. Moreover, the robot is able to respond to touches of its body (e.g. rubbing of its head). ElliQ by Intuition Robotics (production scheduled for the end of 2018) focuses on elderly users and attempts to offer an active aging companion.

In contrast to the previous robots, Buddy by Blue Frog Robotics is mobile and has an arm equipped with a miniature projector. Another approach could be represented by KOMPAÏ-2 (KOMPAÏ robotics)[5], which is a healthcare robot able to provide standing/walking support and to carry small items, which user may put into its tray.

There are also various robots wholly focused on the telepresence functionality as e.g. Beam by Suitable Technologies. A humanoid-like robot by Softbank Robotics – Pepper, is currently not being used in private households; however, rather in shops or offices to invite customers, etc. It attempts to recognize an emotional state of its interlocutor and adapts his behavior accordingly. The arms are mainly used for gesturing, although also able of a basic manipulation with objects.

There also exist narrowly specialized robots as e.g. Paro by PARO Robots – a therapeutic robot with the appearance of a baby seal, capable of sensing touch, heat and sounds.

Within the field of industrial collaborative robots, the greatest attention is naturally given to the safety features of the robots. The collaborative robots are designed either in a way that they do not have enough power to harm a human co-worker (ABB Yummi, Rethink Robotics Baxter/Sawyer), or their power could be limited to allow a collaborative operation (Universal Robots URx, Kuka LBR iiwa/iisy).

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[5] The robot is currently available for evaluations and pre-deployments.

The robots usually have ability of sensing collisions through measurement of joint torques and are able to stop their operation in case of an unwanted contact with an obstacle. There exist various approaches to further enhance safety of collaboration. For instance, Yummi has a soft foam padding, Rethink Robotics robots uses a special type of actuators (Series Elastic Actuators) able to absorb energy and Franka Emika uses a torque-based control (in contrast to a more common velocity or position-based control).

There also exist various third party solutions – e.g. a padded cover with tactile and capacitive sensors (MRK-Systeme SafeInteraction, Blue Danube Robotics AIRSKIN). The usage of capacitive sensor enables robot to sense the immediate proximity of a human co-worker and stop even before actual contact occurs. A similar device (Faude 3D COLLISION PROTECTION) is available also for UR5 robot.

Although some of the robots have integrated vision (Yummi, TM5) or obstacle sensors (sonar in case of Baxter), they are not able to sense its human co-worker and adapt their motions accordingly (trajectories are pre-programmed anyway). Commonly, an external safety sensor as e.g. a laser curtain is utilized whose output signal may slow down or shut down the robot if the worker disrupts the perimeter.

A physical interaction with robots is rare and mainly occurs exclusively during programming – in case of the robots which support a lead-through teaching of waypoints/trajectories. A limited number of robots are specifically design with interaction in mind, e.g. with integrated input/output interaction elements. An example could be Baxter, which posses LCD displaying an animated face able to convey a current state of the robot (where e.g. confused face means error or misconfiguration). Moreover, the display may show a robot's program. The robot also has some LEDs (Attention/-Condition Ring) and controls (Training Cuff, Navigator). It is possible to program the robot solely using these controls and the integrated display without any external device. However, fine-details or complicated tasks has to be anyway programmed offline (using Intera Studio). Another example of the robot with integrated control could be Franka Emika (Franka Pilot).

There even exist accessories to retrofit non-interactive robots, e.g. a light and sound devices mountable on robot's flange (Alumotion YOUring, Faude ProLight). The flange adapter could be also equipped with buttons to simplify some common tasks during programming (switch to a zero gravity mode, store current position, etc.).

## 3.3 GENERAL STATE OF THE ART SUMMARY

The previous sections provided an overview of the current state of the art solutions on the field of HRI. From this overview, it seems that HRI is still quite limited and there is a great potential for improvements enabling a closer teamwork between human users and robots. The chosen solution within this thesis is to combine existing approaches in a novel way, in order to realize task-centered interaction suitable for non-expert users. The resulting method is presented in the next chapter.

# METHOD FOR TASK-CENTERED INTERACTION 4

The following chapter introduces a novel method for task-centered interaction, which has been applied and evaluated within two different use cases.

## 4.1 PROPOSED METHOD

The aim of the method is to integrate already existing approaches with a high potential to improve HRI within the intended use cases in order to benefit from the resulting synergic effect. The essential idea of the method is that interaction should happen within the task space (whether it is a real or a virtual one), with the highest possible utilization of already available modalities. The another important aspect of the method is lowering the user's cognitive load by e.g. transferring interaction onto a higher level of abstraction (task-level interaction) and providing just enough information in order to allow the user to fully focus on the task at the hand. The previously stated features also contribute to the suitability of the method for non-expert users for which the method is explicitly intended. To the best of my knowledge, the method represents a novel approach to the HRI. The method is defined by its following key characteristics.

*Interaction elements embedded into the scene.*

Originating in ecological user interface design methodology, aimed on lowering user's cognitive load and attention switches. Could be achieved by usage of the mixed reality approach.

*Utilization of robot-integrated capabilities.*

Utilization of robot capabilities as a sensing of the environment or an automated motion planning enables the task-level interaction – effectively reducing demands on the user as e.g. less inputs are required. Moreover, integrated safety features as e.g. a collision avoidance or an environment-aware motion planning could reduce stress for the users and allow them to focus on the task at the hand rather then on continuous checking whether the robot performs safely. In order to achieve this, advanced perception capabilities are needed.

*Communication of the robot inner state.*

In order to make the robot's actions predictable and understandable by the user, it is inevitable to e.g. visualize its inner state, particularly perception (which objects or obstacles are detected), intentions (goal of the current movement) and current execution status (waiting for user input, error situation). Communication of the relevant robot inner states to the user could also lead to increased safety (user is aware of what the robot is doing at the moment and may avoid potentially dangerous situations) and spatio-temporal context awareness – lowering demands on a short-term memory and thus lowering workload.

*Context-sensitive user interface.*

The interface should present the right information at the right time, according to the current task and environment state instead of presenting excessive amount of information all the time. A limited amount of the context-relevant information helps to maintain a reasonable mental load.

*Task-appropriate modalities.*

Input and output modalities selected according to the task and its specifics. Maximize utilization of already present modalities as robot arm, or user's body (e.g. sensing pose and activity of the user). Bring as much as possible of the interaction into the task-space by making it interactive itself.

Although individual above mentioned characteristics have been already utilized in some form in the existing literature (see Chapter 3), their combination has not yet been used. The named characteristics when used jointly, allow rich and close HRI.

## 4.2 APPLICATION AND EVALUATION

The proposed method was used to direct design of the user interface for teleoperation of semi-autonomous service robots. The single-window interface is based on integrated 3D virtual scene. The scene consists of visualization of continuously updated 3D model of the remove environment, robot model and various interaction elements. Interactive in-scene elements serve for two main purposes: navigation and manipulation. A user may freely choose from various interaction methods with variable level of autonomy according to current needs. For instance, the user may set waypoints for the robot and it navigates there autonomously (planned trajectory is visualized) or directly teleoperate the robot (with support of the collision avoidance system). When performing a manipulation task, the interface guides the user through the process step by step. For both navigation as well as manipulation tasks, a 3D mouse is used. The control using the mouse is transformed using the non-linear formula and adjusted according to the current 3D scene viewpoint so it provides an easy to use and intuitive input modality. Optionally, a stereoscopic visualization is available in order to convey depth perception cues. The interface in full detail and its evaluation process is further described in the [43].

The method was also applied to the problem of industrial robot programming. In particular, to the use case of a worker's robotic assistant. In this case, interaction happens within the shared workspace, centered around an interactive workshop table with ISAR. The interface allows an ordinary skilled worker to parametrize the robot's program, e.g. to adapt it to changes in production. The ISAR is used to visualize robot perception, display context-relevant notifications and finally, to show explicitly the robot's program. The program visualization allows to switch between steps during learning phase and it shows a current instruction (including its context, i.e. previous and following program instruction) during an execution phase. Among the interactive table, robot arms might be used as input devices (e.g. for tasks requiring 3D data input). The interface design started with Wizard of Oz (WoZ) experiment further described in [41]. The goal of the experiment was to reveal a relationship between a input error rate and a user preference for various modalities. After that, the target use case and the initial scenario were specified (see [42]) and the initial prototype of the system was developed. In order to evaluate the method and uncover usability issues of the prototype, a lab experiment was carried out with six regular workshop workers. The current state of the system and the experiment are further described in [44].

# DISCUSSION AND CONCLUSIONS 5

## 5.1 ACHIEVEMENT OF RESEARCH OBJECTIVES

The research objectives were formulated in order to gain support for the claimed research statement. The following sections provide overview on how each research objective was fulfilled.

*1. Define an integrative method for close human-robot interaction.*

Based on the current state of the art, a novel method has been proposed. The method combines various already existing approaches in an original and previously unpublished way and provides a solid basis for design of advanced user interfaces. The method is specifically intended to allow non-expert users to accomplish non-trivial tasks within the use cases of remote operation of assistive robots and collaboration with industrial robots. It is sufficiently general, which allows application to other use cases; however, this remains as a challenge for the future work.

*2. Apply the method within the contexts of interest.*

The method was applied to the design of two user interfaces: the interface for remote operation of assistive service robots and the interface for collaborative industrial robots. For each application, it was necessary to take into account specifics of the use case, e.g. remote operation in one case and collocated interaction in the other. Despite this, all the key characteristics of the method were used.

*3. Investigate if and how underlying autonomy could support human-robot interaction*

Both developed interfaces heavily rely on an underlying autonomy, or other robot-integrated capabilities. For instance, the interface described in [43] uses continuously updated 3D model of the environment helping to overcome narrow field of view of the robot's main 3D sensor. Interface with visualization of global 3D mapping showed a clear temporal advantage for certain search and navigation tasks. Within the interface, both teleoperation as well as telemanipulation relies on integrated motion planning and collision avoidance in order to lower user's cognitive load.

The interface for robot programming (see [44]) uses robot cognitive capabilities (ability to detect objects in its workspace) and on the fly motion planning to simplify process of programming as well as provide aid during task collaboration.

Although the influence of underlying autonomy usage was not investigated explicitly, both interfaces were successful (in the sense that users were able to solve tasks relatively easily and rated the interfaces positively) and therefore it could be concluded that utilization of underlying autonomy leads to improved HRI.

*4. Investigate what modalities are appropriate for convenient interaction*

The user preference of different modalities considering a variable amount of (synthetically induced) interaction errors for setting the most common parameters in industrial robot programming use case was the main focus of the research paper [41]. From five input modalities, gestures and the touch sensitive table were the two most preferred ones. The gesture-based control was used for some preliminary experiments (see [42]).

The touch sensitive table was later integrated into a fully functional prototype of interactive shared workspace. During the prototype evaluation, some specific usability issues related to the touch-sensitive table modality were identified (see [44]) and should be taken into account for future designs. The prototype used SAR for visualization (output modality) and together with the touch-sensitive table formed the ISAR interface, which was rated as highly intuitive.

Interaction modalities were also considered when designing the teleoperation interface for semi-autonomous assistive robot (see [43]), where the 3D mouse was selected as a suitable device for given tasks: teleoperation and setting the desired end effector pose. A non-linear transformation was applied to data from the 3D mouse to allow precise as well as fast movements. Further, control was adjusted according to the current 3D scene viewpoint (user's perspective) to make interaction more intuitive.

*5. Investigate how the joint task should be presented to make it comprehensive and how to support situation awareness*

Within the assistive robot use case, there is actually no exact procedure to be followed as the way of solving the problem depends on the operator's decision, who can use various tools according to personal preference and the problem at the hand. The interface is built upon ecological approach enabling the operator to directly infer possible actions from visualization of the environment. When the sub-task requires specific steps to be carried out, the interface provides textual guidance and automatically switches to proper visualization according to the task state. For analogical use cases, providing an operator with freedom to choose suitable approach and tools seems appropriate in order to maximize benefit from usage of operator's cognitive abilities.

On the other hand, interaction within the industrial use case could be strictly limited to the exact order of steps, e.g. given by technological process or limitations. For this case, task representation internally based on ROS messages and visualization based on ISAR has been developed. Moreover, the same interface allows both visualization of the task progress during its execution as well as setting of parameters for individual instructions. The program visualization is designed in a way that it provides context to the current instruction in a form of showing also previous and following instruction. In order to improve the situation awareness, there are short textual notifications and visualization of robot intentions where e.g. an object to be manipulated is highlighted.

*6. Evaluate the method-based interfaces with non-expert users.*

The interface for remote operation of assistive robots was thoroughly evaluated within the SRS project. The interface was tested out by a 81 non-expert users in total, both under simulation and within the real conditions. Some first evaluations served to figure out usability problems and to refine the interface. Later, two larger studies with more specific research questions were carried out: one was focused on comparing two modes of 3D environment visualization for solving remote navigation problems and the other one on potential utility of stereoscopic visualization for solving remote manipulation problems. In both studies, the tasks were realistic and far from trivial. Despite that, all users were able to finish all tasks and also the qualitative measures obtained were encouraging.

The interface for industrial robots allows non-expert users to program the robot and to collaborate with it on non-trivial tasks – it was evaluated on task consisting of 32 instructions with 30 parameters to be set in total. However, there are still some unsolved usability issues left for the future work. Although all users were able to solve the tasks, at least 4 moderator's interventions were required during setting program parameters and 2 during program adaptation task, which indicates potential for improvement.

## 5.2 CONCLUSIONS

There exist various solutions for HRI; however, many of them are not suitable for non-expert users, are constrained to basic tasks only or does not deal with close interaction. At the same time, robots are becoming more and more complex as their functionality and abilities to sense are expanding. There is a great challenge on how to utilize those features to maximize benefit for the human-robot team, whether it is a worker and its robotic collaborator in a factory or an assistive service robot helping an elderly person at home and its remote operator. Within this thesis, the central idea on how to face this challenge is formulated as the thesis statement. The specific approach supporting the statement was found by fulfilling the research objectives.

The selected direction of the research within this thesis was to realize a task-centered interaction. In other words, to embed the interface into the task-space, which is possible e.g. by using a mixed-reality approach. The method defined by several key characteristics was formulated. Two different user interface designs for two different use cases were implemented and evaluated with non-expert users, who were (without excessive training) able to achieve non-trivial tasks. Successful evaluation of the two implemented interfaces within different use cases and under different conditions (robot, environment, spatially co-located / remote interaction) indicates potential of the method as well as solid support for the thesis statement. The defined key characteristics may be seen as guidelines for design of forthcoming user interfaces.

## 5.3 FUTURE WORK

In the follow up research, I will mainly focus on interaction with collaborative industrial robots, as currently, this context seems to have a higher potential for real-world applications compared to the context of assistive service robots. In particular, I will focus on improved task understanding and awareness, which is of great importance for complex collaborative tasks. It would be interesting to investigate if and how the ISAR approach could be combined with another mixed-reality approaches as head-mounted displays and how it could be extended to non-flat surfaces.

Another direction of research will be to investigate if and how the proposed method could be extended in order to make HRI adaptable according to the current internal state of a user. For instance, measurement of a user's physiological state as heart rate could improve HRI by allowing the system to react on estimated cognitive workload of a user. Also, as all evaluations so far happened under highly controlled laboratory conditions (which might be seen as limitation of the conducted research), it would be desirable to carry out an out of the lab experiment, preferably a long-term one, to gain more insight into potential technical and usability issues, under the real conditions.

Naturally, the long-term goal is to bring the results of the research into a real-world applications, thereby help to accelerate adoption of collaborative robots, improve working conditions of workers and finally, to contribute to the peaceful future relationships between humans and robots in general.

# BIBLIOGRAPHY

[1] Sonya Alexandrova, Maya Cakmak, Kaijen Hsiao, and Leila Takayama. Robot programming by demonstration with interactive action visualizations. In *Robotics: science and systems*. Citeseer, 2014.

[2] Sonya Alexandrova, Zachary Tatlock, and Maya Cakmak. Roboflow: A flow-based visual programming language for mobile manipulation tasks. In *Robotics and Automation (ICRA), 2015 IEEE Int. Conference on*, pages 5537–5544. IEEE, 2015.

[3] Rasmus S Andersen, Simon Bøgh, Thomas B Moeslund, and Ole Madsen. Task space hri for cooperative mobile robots in fit-out operations inside ship superstructures. In *Robot and Human Interactive Communication (RO-MAN), 2016 25th IEEE International Symposium on*, pages 880–887. IEEE, 2016.

[4] Ronald T Azuma. A survey of augmented reality. *Presence: Teleoperators & Virtual Environments*, 6(4):355–385, 1997.

[5] Gal Bejerano, Gregory LeMasurier, and Holly A Yanco. Methods for providing indications of robot intent in collaborative human-robot tasks. In *Companion of the 2018 ACM/IEEE International Conference on Human-Robot Interaction*, pages 65–66. ACM, 2018.

[6] Mark Billinghurst, Adrian Clark, Gun Lee, et al. A survey of augmented reality. *Foundations and Trends® in Human–Computer Interaction*, 8(2-3):73–272, 2015.

[7] Laura Boccanfuso, Quan Wang, Iolanda Leite, Beibin Li, Colette Torres, Lisa Chen, Nicole Salomons, Claire Foster, Erin Barney, Yeojin Amy Ahn, et al. A thermal emotion classifier for improved human-robot interaction. In *Robot and Human Interactive Communication (RO-MAN), 2016 25th IEEE International Symposium on*, pages 718–723. IEEE, 2016.

[8] Christopher Bodden, Daniel Rakita, Bilge Mutlu, and Michael Gleicher. Evaluating intent-expressive robot arm motion. In *Robot and Human Interactive Communication (RO-MAN), 2016 25th IEEE International Symposium on*, pages 658–663. IEEE, 2016.

[9] Jonathan Bohren, Chris Paxton, Ryan Howarth, Gregory D Hager, and Louis L Whitcomb. Semi-autonomous telerobotic assembly over high-latency networks. In *The Eleventh ACM/IEEE International Conference on Human Robot Interaction*, pages 149–156. IEEE Press, 2016.

[10] Elsa Bunz, Ravi Teja Chadalavada, Henrik Andreasson, Robert Krug, Maike Schindler, and Achim Lilienthal. Spatial augmented reality and eye tracking for evaluating human robot interaction. In *RO-MAN 2016 Workshop: Workshop on Communicating Intentions in Human-Robot Interaction, New York, USA, Aug 31, 2016*, 2016.

[11] Michael D Coovert, Tiffany Lee, Ivan Shindev, and Yu Sun. Spatial augmented reality as a method for a mobile robot to communicate intended movement. *Computers in Human Behavior*, 34:241–248, 2014.

[12] Kerstin Dautenhahn. The encyclopedia of human-computer interaction, 38. human-robot interaction.

[13] Michiel de Jong, Kevin Zhang, Aaron M Roth, Travers Rhodes, Robin Schmucker, Chenghui Zhou, Sofia Ferreira, João Cartucho, and Manuela Veloso. Towards a robust interactive and learning social robot. In *Proceedings of the 17th International Conference on Autonomous Agents and MultiAgent Systems*, pages 883–891. International Foundation for Autonomous Agents and Multiagent Systems, 2018.

[14] Mica R Endsley. Automation and situation awareness. In *Automation and human performance*, pages 183–202. Routledge, 2018.

[15] David Fischinger, Peter Einramhof, Konstantinos Papoutsakis, Walter Wohlkinger, Peter Mayer, Paul Panek, Stefan Hofmann, Tobias Koertner, Astrid Weiss, Antonis Argyros, et al. Hobbit, a care robot supporting independent living at home: First prototype and lessons learned. *Robotics and Autonomous Systems*, 75:60–78, 2016.

[16] Jeff Fryman and Bjoern Matthias. Safety of industrial robots: From conventional to collaborative applications. In *Robotics; Proceedings of ROBOTIK 2012; 7th German Conference on*, pages 1–5. VDE, 2012.

[17] Markus Funk, Andreas Bächler, Liane Bächler, Thomas Kosch, Thomas Heidenreich, and Albrecht Schmidt. Working with augmented reality?: a long-term analysis of in-situ instructions at the assembly workplace. In *Proceedings of the 10th International Conference on PErvasive Technologies Related to Assistive Environments*, pages 222–229. ACM, 2017.

[18] Brian Gleeson, Katelyn Currie, Karon MacLean, and Elizabeth Croft. Tap and push: Assessing the value of direct physical control in human-robot collaborative tasks. *Journal of Human-Robot Interaction*, 4(1):95–113, 2015.

[19] Michael A Goodrich and Alan C Schultz. Human-robot interaction: a survey. *Foundations and trends in human-computer interaction*, 1(3):203–275, 2007.

[20] Phillip M Grice and Charles C Kemp. Assistive mobile manipulation: Designing for operators with motor impairments. In *RSS 2016 Workshop on Socially and Physically Assistive Robotics for Humanity*, 2016.

[21] Stephen Hart, Paul Dinh, John D Yamokoski, Brian Wightman, and Nicolaus Radford. Robot task commander: A framework and ide for robot application development. In *Intelligent Robots and Systems (IROS 2014), 2014 IEEE/RSJ International Conference on*, pages 1547–1554. IEEE, 2014.

[22] Hooman Hedayati, Michael Walker, and Daniel Szafir. Improving collocated robot teleoperation with augmented reality. In *Proceedings of the 2018 ACM/IEEE International Conference on Human-Robot Interaction*, pages 78–86. ACM, 2018.

[23] Johannes Hoecherl, Thomas Schlegl, Thomas Berlehner, Harald Kuhn, and Britta Wrede. Smartworkbench: Toward adaptive and transparent user assistance in industrial human-robot applications. In *ISR 2016: 47st International Symposium on Robotics; Proceedings of*, pages 1–8. VDE, 2016.

[24] Ifr. International federation of robotics, Mar 2018. URL `https://ifr.org/papers/robots-and-the-workplace-of-the-future`.

[25] ISO 13482:2014. Robots and robotic devices – Safety requirements for personal care robots. Standard, International Organization for Standardization, Geneva, CH, February 2014.

[26] ISO 8373:2012. Robots and robotic devices – Vocabulary. Standard, International Organization for Standardization, Geneva, CH, March 2012.

[27] Alejandro Jaimes and Nicu Sebe. Multimodal human computer interaction: A survey. In *International Workshop on Human-Computer Interaction*, pages 1–15. Springer, 2005.

[28] Kevin Sebastian Kain, Susanne Stadler, Manuel Giuliani, Nicole Mirnig, Gerald Stollnberger, and Manfred Tscheligi. Tablet-based augmented reality in the factory: Influence of knowledge in computer programming on robot teaching tasks. In *Proceedings of the Companion of the 2017 ACM/IEEE International Conference on Human-Robot Interaction*, pages 151–152. ACM, 2017.

[29] Slava Kalyuga, Paul Chandler, and John Sweller. Managing split-attention and redundancy in multimedia instruction. *Applied Cognitive Psychology: The Official Journal of the Society for Applied Research in Memory and Cognition*, 13(4):351–371, 1999.

[30] Slava Kalyuga, Paul Ayres, Paul Chandler, and John Sweller. The expertise reversal effect. *Educational psychologist*, 38(1):23–31, 2003.

[31] C.R. Kothari. *Research Methodology: Methods and Techniques*. New Age International (P) Limited, 2004. ISBN 9788122415223. URL `https://books.google.ch/books?id=hZ9wSHysQDYC`.

[32] Martin Kraft and Markus Rickert. How to teach your robot in 5 minutes: Applying ux paradigms to human-robot-interaction. In *Proceedings of the IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN)*, 2017.

[33] Ernst Kruijff, J Edward Swan, and Steven Feiner. Perceptual issues in augmented reality revisited. In *Mixed and Augmented Reality (ISMAR), 2010 9th IEEE International Symposium on*, pages 3–12. IEEE, 2010.

[34] S Li, J Webb, X Zhang, and CA Nelson. User evaluation of a novel eye-based control modality for robot-assisted object retrieval. *Advanced Robotics*, 31(7):382–393, 2017.

[35] Stéphane Magnenat, Morderchai Ben-Ari, Severin Klinger, and Robert W Sumner. Enhancing robot programming with visual feedback and augmented reality. In *Proceedings of the 2015 ACM Conference on Innovation and Technology in Computer Science Education*, pages 153–158. ACM, 2015.

[36] Sotiris Makris, Panagiotis Karagiannis, Spyridon Koukas, and Aleksandros-Stereos Matthaiakis. Augmented reality system for operator support in human–robot collaborative assembly. *CIRP Annals-Manufacturing Technology*, 65(1):61–64, 2016.

[37] Pat Marion, Maurice Fallon, Robin Deits, Andrés Valenzuela, Claudia Pérez D'Arpino, Greg Izatt, Lucas Manuelli, Matt Antone, Hongkai Dai, Twan Koolen, et al. Director: A user interface designed for robot operation with shared autonomy. In *The DARPA Robotics Challenge Finals: Humanoid Robots To The Rescue*, pages 237–270. Springer, 2018.

[38] Marcus Mast, Michal Španěl, Georg Arbeiter, Vít Štancl, Zdeněk Materna, Florian Weisshardt, Michael Burmester, Pavel Smrž, and Birgit Graf. Teleoperation of domestic service robots: Effects of global 3d environment maps in the user interface on operators' cognitive and performance metrics. In *Social Robotics*, pages 392–401. Springer, 2013.

[39] Marcus Mast, Michael Burmester, Birgit Graf, Florian Weisshardt, Georg Arbeiter, Michal Španěl, Zdeněk Materna, Pavel Smrž, and Gernot Kronreif. Design of the human-robot interaction for a semi-autonomous service robot to assist elderly people. In *Ambient Assisted Living*, pages 15–29. Springer, 2015.

[40] Marcus Mast, Zdeněk Materna, Michal Španěl, Florian Weisshardt, Georg Arbeiter, Michael Burmester, Pavel Smrž, and Birgit Graf. Semi-autonomous domestic service robots: Evaluation of a user interface for remote manipulation and navigation with focus on effects of stereoscopic display. *Int. J. of Social Robotics*, 7(2):183–202, 2015. ISSN 1875-4791. doi: 10.1007/s12369-014-0266-7. URL `http://dx.doi.org/10.1007/s12369-014-0266-7`.

[41] Zdeněk Materna, Michal Kapinus, Michal Španěl, Vítězslav Beran, and Pavel Smrž. Simplified industrial robot programming: Effects of errors on multimodal interaction in woz experiment. In *Robot and Human Interactive Communication (RO-MAN)*, pages 1–6. Institute of Electrical and Electronics Engineers, 2016. ISBN 978-1-5090-3929-6. doi: 10.1109/ROMAN.2016.7745111. URL `http://www.fit.vutbr.cz/research/view_pub.php?id=11106`.

[42] Zdeněk Materna, Michal Kapinus, Vítězslav Beran, and Pavel Smrž. Using persona, scenario, and use case to develop a human-robot augmented reality collaborative workspace. In *HRI 2017*, pages 1–2. Association for Computing Machinery, 2017. ISBN 978-1-4503-4885-0. doi: 10.1145/3029798.3038366. URL http://www.fit.vutbr.cz/research/view_pub.php?id=11301.

[43] Zdeněk Materna, Michal Španěl, Marcus Mast, Vítězslav Beran, Florian Weisshardt, Michael Burmester, and Pavel Smrž. Teleoperating assistive robots: A novel user interface for remote manipulation and navigation relying on semi-autonomy and global 3d environment mapping. *Journal of Robotics and Mechatronics*, 29(2):381–394, 2017. ISSN 0915-3942. doi: 10.20965/jrm.2017.p0381. URL http://www.fit.vutbr.cz/research/view_pub.php?id=10576.

[44] Zdeněk Materna, Michal Kapinus, Vítězslav Beran, Pavel Smrž, and Pavel Zemčík. Interactive spatial augmented reality in collaborative robot programming: User experience evaluation. In *Robot and Human Interactive Communication (RO-MAN)*, pages 330–338. Institute of Electrical and Electronics Engineers, 2018. ISBN 978-1-5386-7980-7. URL http://www.fit.vutbr.cz/research/view_pub.php?id=11619.

[45] George Michalos, Panagiotis Karagiannis, Sotiris Makris, Önder Tokçalar, and George Chryssolouris. Augmented reality (ar) applications for supporting human-robot interactive cooperation. *Procedia CIRP*, 41:370–375, 2016.

[46] Paul Milgram and Fumio Kishino. A taxonomy of mixed reality visual displays. *IEICE TRANSACTIONS on Information and Systems*, 77(12):1321–1329, 1994.

[47] Arne Muxfeldt, Jan Niklas Haus, Jingyuan Cheng, and Daniel Kubus. Exploring tactile surface sensors as a gesture input device for intuitive robot programming. In *Emerging Technologies and Factory Automation (ETFA), 2016 IEEE 21st International Conference on*, pages 1–4. IEEE, 2016.

[48] Curtis W Nielsen, Michael A Goodrich, and Robert W Ricks. Ecological interfaces for improving mobile robot teleoperation. *Robotics, IEEE Transactions on*, 23(5):927–941, 2007.

[49] Chris Paxton, Andrew Hundt, Felix Jonathan, Kelleher Guerin, and Gregory D Hager. Costar: Instructing collaborative robots with behavior trees and vision. In *Robotics and Automation (ICRA), 2017 IEEE International Conference on*, pages 564–571. IEEE, 2017.

[50] Mikkel Rath Pedersen, Lazaros Nalpantidis, Rasmus Skovgaard Andersen, Casper Schou, Simon Bøgh, Volker Krüger, and Ole Madsen. Robot skills for manufacturing: From concept to industrial deployment. *Robotics and Computer-Integrated Manufacturing*, 37:282–291, 2016.

[51] TXN Pham, K Hayashi, Christian Becker-Asano, S Lacher, and Ikuo Mizuuchi. Evaluating the usability and users' acceptance of a kitchen assistant robot in household environment. In *Robot and Human Interactive Communication (RO-MAN), 2017 26th IEEE International Symposium on*, pages 987–992. IEEE, 2017.

[52] Clemens Pohlt, Sebastian Hell, Thomas Schlegl, and Sven Wachsmuth. Impact of spontaneous human inputs during gesture based interaction on a real-world manufacturing scenario. In *Proceedings of the 5th International Conference on Human Agent Interaction*, pages 347–351. ACM, 2017.

[53] Camilo Perez Quintero, Romeo Tatsambon Fomena, Azad Shademan, Nina Wolleb, Travis Dick, and Martin Jägersand. Sepo: Selecting by pointing as an intuitive human-robot command interface. In *ICRA*, pages 1166–1171, 2013.

[54] N.J. Salkind. *Encyclopedia of Research Design*. Number sv. 1. SAGE Publications, 2010. ISBN 9781412961271. URL https://books.google.cz/books?id=pvo1SauGirsC.

[55] Marc Schneider and Barbara Deml. Analysis of a multimodal human-robot-interface in terms of mental workload. In *Advances in Ergonomic Design of Systems, Products and Processes*, pages 247–260. Springer, 2017.

[56] Yasaman Sefidgar, Sarah Elliott, and Maya Cakmak. A system for situated tangible programming of robot skills. In *IROS Workshop on Learning for Collaborative Robotics: Enabling Flexible, Redeployable and Agile Industrial Applications*, 2017.

[57] Yasaman S Sefidgar, Thomas Weng, Heather Harvey, Sarah Elliott, and Maya Cakmak. Robotist: Interactive situated tangible robot programming. In *Proceedings of the Symposium on Spatial User Interaction*, pages 141–149. ACM, 2018.

[58] Sichao Song and Seiji Yamada. Expressing emotions through color, sound, and vibration with an appearance-constrained social robot. In *Proceedings of the 2017 ACM/IEEE International Conference on Human-Robot Interaction*, pages 2–11. ACM, 2017.

[59] Michal Spanel, Zdenek Materna, Vit Stancl, Tomas Lokaj, Pavel Smrz, and Pavel Zemcik. Deliverable d4. 5.2–context-aware virtual 3d display final report. 2013.

[60] Susanne Stadler, Kevin Kain, Manuel Giuliani, Nicole Mirnig, Gerald Stollnberger, and Manfred Tscheligi. Augmented reality for industrial robot programmers: Workload analysis for task-based, augmented reality-supported robot control. In *Robot and Human Interactive Communication (RO-MAN), 2016 25th IEEE International Symposium on*, pages 179–184. IEEE, 2016.

[61] Susanne Stadler, Nicole Mirnig, Manuel Giuliani, Manfred Tscheligi, Zdenek Materna, and Michal Kapinus. Industrial human-robot interaction: Creating personas for augmented reality supported robot control and teaching. In *Proceedings of the Companion of the 2017 ACM/IEEE International Conference on Human-Robot Interaction*, pages 291–292. ACM, 2017.

[62] Gerald Stollnberger, Astrid Weiss, and Manfred Tscheligi. " the harder it gets" exploring the interdependency of input modalities and task complexity in human-robot collaboration. In *RO-MAN, 2013 IEEE*, pages 264–269. IEEE, 2013.

[63] Xiang Zhi Tan, Aaron Steinfeld, and M Bernardine Dias. Communication through movement: An alternative method of interaction for hri, 2016.

[64] Jörn Vogel, Katharina Hertkorn, Rohit U Menon, and Máximo A Roa. Flexible, semi-autonomous grasping for assistive robotics. In *Robotics and Automation (ICRA), 2016 IEEE International Conference on*, pages 4872–4879. IEEE, 2016.

[65] Michael Walker, Hooman Hedayati, Jennifer Lee, and Daniel Szafir. Communicating robot motion intent with augmented reality. In *Proceedings of the 2018 ACM/IEEE International Conference on Human-Robot Interaction*, pages 316–324. ACM, 2018.

[66] Robert H Wortham, Andreas Theodorou, and Joanna J Bryson. Improving robot transparency: real-time visualisation of robot ai substantially improves understanding in naive observers. *IEEE RO-MAN 2017*, 2017.

[67] Sebastian Wrede, Christian Emmerich, Ricarda Grünberg, Arne Nordmann, Agnes Swadzba, and Jochen Steil. A user study on kinesthetic teaching of redundant robots in task and configuration space. *Journal of Human-Robot Interaction*, 2(1):56–81, 2013.

[68] Lihua Xue, CJ Liu, Y Lin, and WJ Zhang. On redundant human-robot interface: Concept and design principle. In *Advanced Intelligent Mechatronics (AIM), 2015 IEEE International Conference on*, pages 287–292. IEEE, 2015.

# ZDENĚK MATERNA

## PERSONAL INFORMATION

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| | *Born in Czech Republic*, 18 May 1986 |
| *email* | imaterna@fit.vutbr.cz |
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## WORK EXPERIENCE

*2010–Present* Embedded Software Developer, EGMedical, s r.o.

Design, implementation and testing of software for custom embedded devices.
Reference: Ing. Ivo Strašil · ivo@strasil.net

## EDUCATION

### *2008-2010* The College of Polytechnics Jihlava

Degree: Bc.
Thesis: *Electronics for the mobile robot*
Description: Design and implementation of custom modules (motor control, user interface and sensor boards) for a mobile robot communicating over RS-485 using a protocol providing basic abstraction in order to simplify higher level control.

### *2010-2011* Brno University of Technology

Faculty of Electrical Engineering and Communication
Degree: Ing.
Thesis: *Positionable stand for surveillance camera*
Description: Soft real-time control of a positionable camera stand over Ethernet using custom built Linux distribution.

### *2011-present* Brno University of Technology

Faculty of Information Technology
PhD. student, focused on human-robot interaction, augmented reality, user experience.

## OTHER INFORMATION

2012 · ROS RoboCup Rescue Summerschool, Technische Universität Graz.

2012-present · Lecturer on ROS Workshop organized by Robo@FIT research group.

2016 · Research visit in Center for Human-Computer Interaction at the University of Salzburg (2 weeks).

## INTERESTS

Raising kids · DIY · Hiking · Photography · Gardening

January 22, 2019