ROBOTS, OBJECTS, HUMANS: TOWARDS SEAMLESS INTERACTION IN INTELLIGENT ENVIRONMENTS

Supporting Complex Cooperative Interactions between Humans and Technical Systems in Real World Scenarios through Cognitive Objects

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Abstract: Future intelligent environments will be inhabited by humans, robots and ‘Smart Objects’ and allow for seamless interaction beyond the desktop. These environments therefore have to be adaptive, self-organizing, provide autonomous reasoning and integrate a variety of heterogenous hardware, objects, sensors and actuators – which goes far beyond merely interconnecting different kinds of technology. In light of the dawn of personal robotics, these environments should be equally usable and supportive for humans and robots. Manipulation tasks involving physical objects are at core of the interaction in these environments. This places novel challenges on the involved ‘Smart Objects’.

We present an approach for supporting robotic systems in the interaction with physical objects while maintaining human usability and functionality by using so-called ‘Cognitive Objects’. We describe our infrastructure to support developing, simulating, testing and deploying of pervasive computing systems, using ROS (Robot Operating System) as middleware, and present several application scenarios. The scenarios are not limited to the robotics domain, but include location-aware services, intelligent environments and mobile interaction therein. Based on our experience, recommendations for the design of ‘Cognitive Objects’ (CO) and environments are given, to address the individual strengths of humans and machines and to foster new synergies in shared human-robot environments.

1 INTRODUCTION

In the last decade, the transition from the classical PC towards interaction beyond the desktop has begun and is still ongoing. Our smartphones are our daily companions, our homes become ‘smart’ through embedded sensors and actuators, networking between appliances, and automation. We currently experience the dawn of personal robotics supporting humans in everyday life, be it for entertaining purposes or for elder care scenarios. Unlike highly specialized industrial robots, the spread towards private households requires multi-functionality and openness to a broader spectrum of application areas. Service robots are intended for use in highly dynamic real-world environments. They need to operate electronic devices, interact with arbitrary objects, and with people. Therefore, robots need to be aware of their environment and gather information about it. Today’s sensor- and particularly vision-based techniques for object detection are not always sufficient for these scenarios, or have too high computational demands to work in real-time.

This illustrates a major challenge in the Ubicomp vision: interaction takes place through objects and object manipulation. In robotic environments, objects therefore need to be designed differently to fit the needs of both humans and robots. In this paper, we present an approach for supporting robotic systems in interaction with physical objects by introducing so-called *Cognitive Objects*, maintaining human usability at the same time. We demonstrate example scenarios for leveraging interaction between humans, robots and objects in our intelligent environment, the *Cognitive Office*. We identify strategies for the adaption of everyday technology for the needs of humans and technical systems, and provide design recommendations for objects and environments for more seamless interaction and applicability for humans and robots.

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2 COGNITIVE OBJECTS AND COGNITIVE OFFICE

We present the concept of *Cognitive Objects* (Möller et al., 2011) and briefly distinguish them from related research. Subsequently we introduce the intelligent environment our *Cognitive Objects* are embedded in and summarize the conjoint research goals.

2.1 Definition of Cognitive Objects

We define Cognitive Objects as *physical artifacts embodied in an interaction which include sensors, actuators, communication and computation, to equally support humans and robotic systems in task execution*. This definition comprises that *Cognitive Objects*

- are physical, unambigously identifiable objects
- are embodied in the environment and the task they are involved in
- include cognition through sensors, and disclose information through appropriate actuators
- incorporate communication abilities like Wireless Sensor Nodes (WSNs)
- proactively and situatedly collaborate with humans, robots and the environment to assist in task execution.

Their cooperative nature constitutes a new way to bridge the gap in interaction between humans and machines, respecting both human affordances and machine requirements.

2.2 Related Work on Smart Objects

The idea of augmenting artifacts by digital functionality has been followed with *Smart Objects* (Kranz and Schmidt, 2005; Beigl and Gellersen, 2003) or tangible user interfaces (Ullmer and Ishii, 2000). Their focus is to move computer interaction away from the WIMP paradigm (windows, icons, menus and pointer) towards an integration of technology into everyday context and devices. Examples are smart pushpins on noticeboard to stimulate recall (Laerhoven et al., 2002), a camera-enhanced cabinet to assist humans in object retrieval (Siio et al., 2003) or edutainment toys (Kranz et al., 2005). While these concepts focus on humans and HCI, augmented objects for mixed human-robot environments must by design equally support humans and robots.

Smaller *Smart Objects* are used in the context of interactive spaces, so-called intelligent environments (Linner et al., 2010) emerging due to the availability of embedded computing (Kranz and Schmidt, 2005).

Figure 1: The *Cognitive Office*, our intelligent cognitive environment in 3D simulation. Physical objects like drawers, windows, doors and plants and corresponding events are linked to their virtual representations in real-time.

Such sensor-and actuator-augmented rooms can be the basis for ambient assisted living (Kranz et al., 2010c) or location-based services. The sensor networking platforms used in this context, e.g. Smart-Its (Holmquist et al., 2004) or Motes[1], communicate wirelessly with other *Smart Objects* in their environment dynamically, collect data and perform signal processing. They consist of standardized hardware and are not unique like *Cognitive Objects*, and are not intended for direct human interaction.

Further information and a detailed discrimination of *Cognitive Objects* from other smart object research can be found in (Möller et al., 2011). Comparisons to related work will also be made in the respective locations later in this paper.

2.3 Cognitive Office: An Intelligent Environment

The *Cognitive Office* (Fig. 1) is a live-in lab at our institute with a multitude of distributed objects, systems, sensors, and actuators working together. This 'intelligent environment' allows for rich and embedded interaction (Kranz et al., 2010b) beyond the desktop and provides context-sensitive services to its human users, the sum of its cooperating systems and artifacts being more than the individual parts.

The *Cognitive Office* is augmented by various sensors and communication technologies:

- Local sensors and actuators, e.g. for temperature and light; contact switches for windows, doors or drawers; PIR sensors for presence detection, power switches
- Internet-based services (e.g. traffic, weather, ...)
- Cognitive Plants[2]

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[1] http://www.xbow.com

[2] http://www.botanicalls.com, http://www.koubachi.com

An in-depth discussion of this intelligent environment and its technical basis can be found in (Roalter et al., 2010).

2.4 Software

The set of software and tools we use for the development, simulation, deployment and evaluation of ubiquitous services and intelligent objects in the context of the *Cognitive Office* consists of three components: middleware, visualization and simulation.

Middleware. ROS (Robot Operating System) as underlying middleware interconnects sensors, actuators and all interacting entities in the *Cognitive Office*. ROS is a meta-operating system initially designed for robots (ROS, 2010), but equally applicable for an intelligent environment. Being a heterogeneous, distributed sensor-actuator system, such an environment can be considered as immobile robot (Williams and Nayak, 1996). The ROS framework builds upon and abstracts from different underlying systems, containing packages that abstract from heterogenous hardware, provide low-level control and message-passing and already implement a wide range of commonly used functionality, such as controlling a mobile robot.

Visualization. Visualization tools are not only useful as actuators (e.g. for digital door signs, user feedback on appliances or status monitoring), but serve also as a means to visualize received sensor data. It can be evaluated how a room or an environment "looks like" for a device that only has certain sensors, and allows the evaluation of cognition-based systems in simulated and real intelligent environments. It thereby does not play a role whether the visualization output is local or remote.

Simulation. Using simulation tools (e.g. Gazebo[3]), interaction between robots, objects, sensors, and humans can be re-, but also *pre*constructed, i.e. simulated before the actual deployment, using a realistic physics engine including collision detection and realistic forces. Building upon standardized object interchange formats, objects can be designed with external modeling tools and imported so that the realistic reconstruction of real-world environments is possible. Special items, such as robots, e.g. the Personal Robot 2 (PR2) by Willow Garage[4] or mobile phones can be imported as predefined objects.

Using ROS in the context of intelligent environments has several benefits compared to other middleware. An overview of Ubiquitous Computing middleware can be found in (Kranz et al., 2007).

Coverage. While many approaches are tailored to a proposed scenario, ROS covers a wide range of use cases (see Sec. 3), and is not limited to these. The support for real robot integration and interaction between robots and the intelligent environment is a benefit compared to middleware not coming from the robotics domain.

Reliability. ROS is in a mature state and is continuously further developed, offering high reliability and frequent updates. Interfaces and APIs are well documented and users benefit from support and exchange in the research community.

Applicability. The presented tools support quick deployment in real-world scenarios, allowing easy application implementation on top of abstractions, models and APIs. Common and frequently used functionality is provided 'out of the box'. A system can be adapted to different setups with low amount of reconfiguration. Simulated and real-world sensor data pass through the same processing chain and cause identical actuator events, allowing to move from testing to deployment without code changes.

Openness and Extensibility. Software and code are open source to enable re-use, allow for code-inspection and standardization, and have a broad basis in the community for shared development. The infrastructure provides means to add both new soft- and hardware (such as new algorithms or sensing technologies). The vividness of the ROS community has recently been proven again by the integration of MS Kinect support in ROS only days after the release of the open source drivers.

2.5 Research Questions and Goals

We pursue the following research questions and goals:

Scenarios. Which scenarios can benefit from the use of *Cognitive Objects* that are augmented by communication technology, based on the current state of research in the areas of robotics and ubiquitous computing? How do such future objects differ from intelligent objects as we understand them today, regarding sensors, actuators, distributed cooperative information processing, communication and interaction?

Influence on Interaction. What is the influence of such objects on processes and activities for humans, robots and mixed environments for interaction between humans, robots and objects, regarding usability, utility, subjective and objective quality of interac-

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[3] www.playerstage.sourceforge.net/gazebo/gazebo.html

[4] www.willowgarage.com/pages/pr2/overview

tion, as well as user transparency and intelligibility?

Relevance for Service Robotics. What is the relevance of such objects for the domain of (service) robotics? In particular, what are the consequences regarding the reduction of interaction complexity, algorithms, incertainty and ambiguity of sensor-based cognition and internal, digital representations of the real world in dynamic, complex environments? What contributions can be made to increase the certainty and reliability of information in robotic perception, and in which other ways can robotic perception be augmented, in order to make phenomena perceivable that today's robots cannot detect at all, or not reliably in all desired scenarios?

Abilities. What are characteristic, necessary and possible abilities and properties of intelligent artifacts like *Cognitive Objects*? What is their respective influence on human and robot interaction with them, and which possibilities do they open up? How can strategies for the selection of appropriate and adequate information and communication technologies (ICT) to be used in such devices and objects be developed?

Development. What are appropriate approaches to support abstraction and representation in the development of such novel objects, both application- and user-centered? Furthermore, how can at the same time the integration of electronic hardware and software methodically be supported and programming and customization be facilitated for the end-user?

Security and Privacy. What consequences arise regarding the additional complexity of products and a possible effect on security and privacy of the end user?

3 APPLICATIONS

We present applications from different fields integrated and deployed in the context of the previously described *Cognitive Office*, comprising approaches from human-object, robot-object and mobile interaction, location- and context-aware services and more (see Fig. 2).

3.1 Human-computer Interaction and Human-robot Interaction

We present three constructed prototypes as examples of *Cognitive Objects* as defined in Sec. 2.1, and integrated them into the *Cognitive Office*[5] (two of them implemented, one simulated).

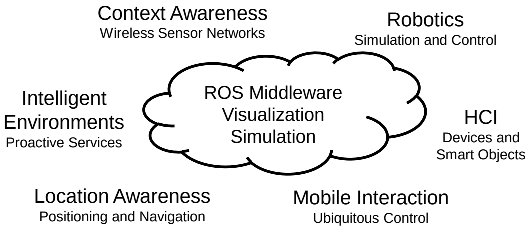

Figure 2: The robotics middleware ROS in combination with visualization and simulation tools can serve as a basis for various applications from different research fields.

Cognitive Cup. The Cognitive Cup is a coffee mug augmented by self-awareness (see Fig. 3). It has an accelerometer to detect its orientation and senses fluid level and temperature of its content. The cup helps robots to track its location and orientation by infrared LEDs (invisibly for human eyes) built into the seam. It communicates wirelessly with its environment via RFID (for identification) and ZigBee (for real-time sensor value transmission). Disclosing this information can assist a grasping robot, e.g. to indicate that the cup has to be handled with care in order not to be spilled. More sophisticated services become possible, such as a robot automatically bringing a new cup when the coffee is cold. The cup still supports human affordances, as it resembles a normal cup in shape, size and weight, and can even be put into the dishwasher (after removing the socket).

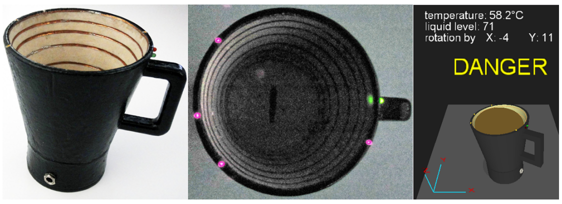

Figure 3: The Cognitive Cup supports human affordances (left) and robot-object interaction through infrared LEDs (middle). Orientation, fluid level and temperature are transmitted wirelessly, here in 3D visualization (right). See a video at www.youtube.com/watch?v=mP3ZbPM9TVU.

Load Table. Information about non-augmented objects and related interaction can be gained through adding cognition to furniture. Load sensing in a wooden table provides three information primitives about objects placed on it: weight, position, and type of interaction based on the load signal shape over time (Schmidt et al., 2002). The table becomes a *Cognitive Object* disclosing information about other objects, while the augmentation is entirely invisible for human eyes. Multiple sensors are networked, middleware-controlled and allow triangulation of ob-

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[5] See the *Cognitive Office* and the implemented *Cognitive Objects* at www.lmt.ei.tum.de/team/kranz/videos.php

ject positions based on measured load values. Additionally placed objects can be detected by comparing the capacitive values to the previous state. The distribution of cognition can assist robots in grasping non-augmented objects which would otherwise be invisible like e.g. glass. The table even detects whether a glass is full or empty by monitoring the weight change. A similar approach with capacitive sensors has been shown in (Wimmer et al., 2007). Currently, the table is integrated into the simulation only.

Whiteboard Cleaning Robot. Whiteboards are often used for quick notes. This robotic whiteboard cleaner autonomously erases the whiteboard, choosing the optimal path to only traverse areas containing text. At the end, it moves automatically to its charging station. Before the cleaning procedure, the whiteboard's content is captured and saved as digital image in order to preserve potentially important information. The whiteboard is thus enhanced to an interactive surface that autonomously makes information written on it persistent. The text can be made digitally accessible and searchable using OCR. Special symbols can provide additional functionality, e.g. the entire whiteboard content can be emailed to a specified address by drawing an envelope symbol. While the cleaning robot in Fig. 4 is an early prototype, in the next iteration the size will be reduced to fit into an everyday, human-usable whiteboard eraser.

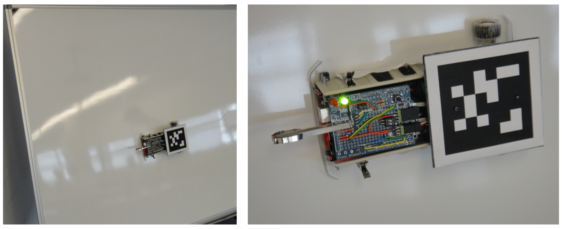


Figure 4: Left: The cleaning robot wiping a whiteboard. Right: The robot navigates autonomously to find the most efficient route and can be camera-tracked. See a video at www.youtube.com/watch?v=hZxd-d1dDE4.

3.2 Context and Location Awareness

The localization of objects supports robot-object interaction (e.g. an object being searched can announce its location) and enable context-sensitive services (e.g. sending a document to the nearest printer). The *Cognitive Office* supports both active and passive localization. Context and location detection using sensors can easily be integrated in the ROS middleware. Passive presence detection (Kranz et al., 2006) can e.g. be realized using PIR sensors or by inference from context information such as open doors or windows with help of a HMM. We use this for automated HVAC, e.g. switching on the fan not only temperature-based, but preferably when the worker leaves the room in order not to distract him by the noise. Another application would be to disable heating while the window is open to save energy.

We implement active location detection by WLAN fingerprinting as indoor positioning system, using triangulation and similarity search from a database of location-annotated WLAN access point signal strengths. Such a system can be the basis for location-aware objects, up to indoor navigation with help of a mobile phone. The *Cognitive Office* and our simulation environment support all stages of such a system's development process. In the planning phase, the 3D simulation of the environment can visualize the relative signal strength (RSS) of the existing WLAN base stations including reflections etc., e.g. using a color-coded map. This can help finding positions for measuring fingerprints and adding them to a database or even to find an optimal initial position of WLAN access points. In a second phase, the positioning algorithm can be tested in the simulation and provide valuable insights about its accuracy and reliability before any real deployment, as not only the floor plan and walls, but also all furniture and objects of the real environment are accurately simulated. Changes can be made easily and tests be rerun, which constitutes an enormous advantage compared to real-world tests in terms of costs and time.

3.3 Mobile Interaction

Mobile phone interaction approaches with the real world have been presented, each with individual drawbacks. Some require the augmentation of objects with tags (visual or RFID), or special hardware, like pointing using a laser (Rukzio et al., 2006). MagicPhone (Wu et al., 2010) uses the phone's gyroscope and accelerometer to detect in which direction it is pointing has been presented. The phone can then be used for remote control or interaction with the targeted device, e.g. send slides to a projector or change TV channels. The position of individual objects in the room needs however to be known, as the phone's orientation is the only clue for detecting which device it is pointing at. For the development and testing of such a system, the whole environment would have to set up, requiring physical space, time and costs.

Our approach using ROS and simulation tools could perfectly support such a setup in simulation and testing. The *MagicPhone* scenario has been realized in simulation in our system to highlight the potential of the proposed toolchain. The model of the mobile phone can be imported in simulation tool and integrated into the virtual environment, which is an exact model of the real-world rooms in which the system is to be tested. Coming from the robotics area, ROS contains methods for remotely controlling robots in an environment, showing the robot's exact field of view in the simulation. These tools can similarly be used for the simulation of a mobile phone carried by a person. Pointing interactions are simulated by controlling the phone model using the PC keyboard, a multi-axis controller or a MS Kinect camera. The object(s) targeted by the phone can easily be detected by viewing the phone's simulated camera image in the simulation.

3.4 Extending Intelligent Environments

Intelligent environments or 'smart spaces' can be defined as multi-user, multi-device, dynamic interaction environments that enhance a physical space by virtual services (Johanson et al., 2002). The aspect of being 'dynamic' comprises the smart space's extension over the borders of an augmented room to wherever the user is, e.g. on the way from and to the office.

The *Cognitive Office* extends its functionality out of the physical office space by receiving a notification from the user's smartphone when he approaches the campus (detected via GPS or the WLAN SSID). The office PC is thereupon booted via Wake-on-LAN, important appointments are shown on the calendar and the email application is launched, ready to use when the user reaches the office. The *Cognitive Office* also takes care of a pleasant trip home: A traffic service knowing the way home proactively searches for traffic news on that route. In case of a traffic jam or accident, this news is reported even before the user is getting in his car. If historically traffic jams occurred frequently at a certain time (e.g. the rush hours), the system proactively suggests the right time to leave the office by self-learning.

3.5 Simulating Robots and Humans

Coming from the robotics domain, the ROS middleware is perfectly suitable for monitoring, controlling and evaluating interaction between robots and humans, objects and the environment. ROS incorporates various methods for robotic control and interaction, as well as drivers for components like vision systems. We use ROS to control the PR2 in the *Cognitive Office* (as seen in Fig. 5 in the 3D simulation).

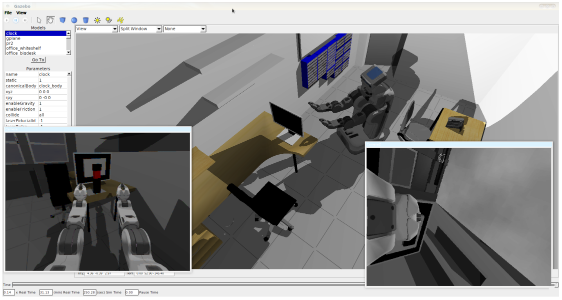


Figure 5: Visualization of a PR2 robot's hand camera views.

Due to the support of complex motion sequences and the integrated physics engine, a bio-mechanical human model can be integrated for simulating interaction with (intelligent) artifacts, robots or any other objects in the virtual environment. ROS supports complete control of arms, head and other parts of the (robot) body, which can be adapted for a human model. Different types of interaction, e.g. pressing buttons, grasping objects, opening doors etc. can be modeled and tested. Models can be controlled by keyboard or another controller, e.g. a joystick. It is imaginable to steer a human model through an accurate model of a 3D simulation and use it to evaluate location-aware systems, e.g. presence detection for proactive context-based services.

The visualization tool allows to monitor the robot's camera views as it moves in real time and thus 'see the world through the robot's eyes'. It is also possible to monitor the sensory input such as the robot's laser scanner, both from the real world and the simulation. This allows to simulate a robot exploring an unknown environment and to record the data it captures before any deployment in the real world, which constitutes valuable information for evaluating whether e.g a service robot would get along in a domestic environment.

3.6 Interconnection

All examples just described are *not* individual applications put together in one room, but share the same middleware and can communicate with each other. The ROS publish/subscribe architecture lets arbitrary components use any data and service available to the middleware, allowing for a new stage of smart services, and interaction between objects, robots and humans.

4 DESIGN GUIDELINES

We have presented our research goals to leverage human-robot and robot-object interaction in the *Cognitive Office* with help of *Cognitive Objects*. We have presented examples from various contexts that we have successfully developed, designed and tested with help of this environment. In the remainder of this paper, we draw first conclusions from our experiences and deduce guidelines for the design of intelligent artifacts and environments that support interaction between humans, objects and robots. We begin with comparing the abilities and characteristics of human and machines, and afterwards give recommendations for how objects and environments could be designed to play out the strengths and compensate the weaknesses of humans and computerized systems for more effective interaction, collaboration and cooperation.

4.1 Human-machine Comparison

As a basis for the later recommendations, the differences between humans and machines in terms of their unequal abilities are described.

4.1.1 Human Abilities and Machine Abilities

The following classifications (Chapanis et al., 1951) have been made in the context of aviation in order to choose whether functions can be controlled by machines or are better operated by humans. These observations also apply for today's computerized systems and support function allocation in intelligent environments. Humans surpass machines in their ability to

- detect small amount of visual and acoustic energy
- perceive patterns of light or sound
- improvise and use flexible procedures
- store very large amounts of information for long periods and to recall relevant facts at the appropriate time
- reason inductively
- exercise judgment.

Machines appear to surpass humans with respect to the ability to

- respond quickly to control signals, and to apply great force smoothly and precisely
- perform repetitive, routine tasks
- to store information briefly and then to erase it completely
- to reason deductively, including computational ability
- handle complex operations, i.e. to do many different things at once.

4.1.2 People versus Machine-centered Views

The above abilities appear differently depending on the point of view. From a machine-centered view, people are inexact, often act illogically or emotionally. Machines, by contrast, are always precise, orderly and logical. However, from a people-centered view, machines lack essential abilities, such as creativity, imagination or adaptability, are 'dumb', while humans are resourceful, creative and attentive to changes. The fact that the strengths of one party are weaknesses of the other (see Fig. 6) needs to be considered in the design of objects and environments conjointly used by humans and machines.

	People are	Machines are
Machine-centered view	• vague • disorganized • distractible • emotional • illogical	• precise • orderly • undistractible • unemotional • logical
People-centered view	• creative • compliant • attentive to changes • resourceful • able to make flexible decisions based on context	• dumb • rigid • insensitive to change • unimaginative • constrained to make consistent decisions

Figure 6: Humans and machines have different abilities which are – depending on a people-centered or machine-centered view – strengths or weaknesses. Intelligent environments should both humans and computers support in their strengths, and compensate their weaknesses. Tabular representation according to (Norman, 1993).

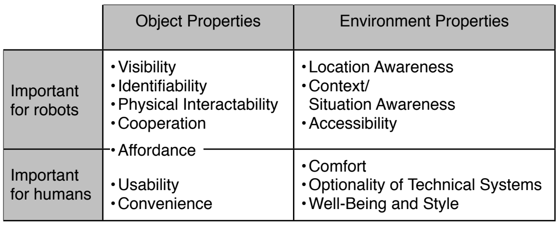
4.2 Recommendations

Based on human and machine abilities and our experience in the *Cognitive Office*, we present initial recommendations for the design of intelligent environments and *Smart Objects*. We identify object and environment properties, and classify them according to their importance for humans and robotic systems, as summarized in Fig. 7. Objects and environments intended for a conjoint use by humans and robots should respect the recommendations from both categories.

4.2.1 Important Object Properties

Smart Objects should respect the following properties to support interaction with robotic systems:

Visibility. The first precondition for interaction is the object's visibility to a robot, being a challenging task for computer vision systems when the object is transparent or has glossy and shiny surfaces. Small objects might be hardly distinguishable. Low-light



	Object Properties	Environment Properties
Important for robots	• Visibility • Identifiability • Physical Interactability • Cooperation	• Location Awareness • Context/ Situation Awareness • Accessibility
	• Affordance	
Important for humans	• Usability • Convenience	• Comfort • Optionality of Technical Systems • Well-Being and Style

Figure 7: Objects and environments for shared robot and human use should support specific aspects, some of them being especially important for humans or for computerized systems.

environments, shadows or occlusions (e.g. because of other objects in the line of sight or the robotic arm in the way) can aggravate the problem. Objects can support such situations by ‘I am here’ self-disclosement, e.g. by built-in RFID tags or infrared LEDs invisible for humans.

Identifiability. Beyond being visible, objects need to be identifiable by robots as *specific* object out of many similar ones. This could likewise be realized using RFID tags, as demonstrated in our Cognitive Cup. Invisible technology like RFID helps maintaining the object’s initial appearance, while visual tags like QR codes can also be useful for humans, serving as an indicator for embedded functionality.

Physical Interactability. Objects need to support physical interaction with robots, e.g. be graspable by robotic hands. Not only the shape of the object and possible handles need to be formed accordingly, the robot needs to know *how* to grasp it (e.g. a cup filled with hot coffee needs to be grasped differently than an empty cup, which can also be picked up on the handle with the open side hanging down). *Cognitive Objects* can assist interaction by disclosing information about their internal state, e.g. whether a cup is empty or not. Moreover, infrared LEDs can, invisibly for humans, support pose estimation for a robot, which eases the task of targeting it. The object can be adapted to the needs of robot interaction, as long as it does not negatively affect human interaction. The surface of our Cognitive Cup is e.g. rougher than a porcelain mug, in order to facilitate grasping by a robot hand.

Cooperation. Objects should cooperate in interaction with robotic systems, instead of leaving cognition and computation all to the robot. The distribution task execution conforming the *Ubiquitous Computing* vision (Weiser, 1991) is more efficient in terms of computational power and more effective. *Cognitive Objects* follow this paradigm (see (Möller et al., 2011) for more detailed information).

Affordance. The term of affordance is placed at the intersection of humans and machines in Fig. 7, as it is equally important for both of them. In usability and UI design, affordance denotes the ability of an object to explain itself (Norman, 1990), i.e. to make intelligible to an interacting person what it is for and how to use it. Humans know – based on their experience – how to use e.g. a teapot and where to grasp it when hot. Robot-usable everyday objects need special affordances, which have been subject to research e.g. in (Duchon et al., 1994) and (Fitzpatrick et al., 2003). Affordances for robots can be realized by disclosing their purpose and usage instructions in a machine-understandable way. *Cognitive Objects* incorporating sensors, actuators, computation and communication are a means to provide this semantical knowledge.

The augmentation for robot usability must not go along with replacement, but coexistence of human affordances. Just as human affordances are ‘invisible’ for robots, parts relevant only for technical systems (like e.g. antennas) should be hidden from human eyes.

For human usage, *Smart Objects* should respect

Usability. To be practical and simple to use for humans, interaction design, cognitive psychology and cultural factors should be considered in the design progress. Consider an ‘intelligent’ cup signaling the temperature of its content. While the cup internally possibly works with a numeric temperature scale, the temperature might be glimpsed more intuitively by a person if it is translated into a color scale (red = hot, blue = cold), instead of just showing the numeric temperature value on a display.

Convenience. Augmented objects must not reduce convenience compared to conventional, non-augmented objects. When e.g. the battery is drained, the object should still offer its non-technical functionality, instead of not being usable at all.

4.2.2 Important Properties for Environments

For an intelligent environment being used by robotic systems, the following factors are of importance:

Location Awareness. For a human, it is self-evident to know whether he is in the kitchen or in the living room, while for a robot, it isn’t. Intelligent environments suitable for robots thus should support location awareness for computerized entities. They can e.g. be equipped with multiple WLAN base stations to enable WLAN fingerprinting, or offer positioning using DECT (Kranz et al., 2010a), especially for *Cognitive Objects*.

Context Awareness. Intelligent environments aim at facilitating people’s everyday life by context-aware services and applications. The environment can support machines in providing this context awareness, e.g. by providing the respective sensors to detect different sorts of events, such as presence by motion sensors, opening or closing of windows, doors and drawers by contact switches, etc.

Accessibility. In a mixed human-robot environment all rooms and areas must be accessible by robotic locomotion systems. While some robots are able to use stairs, for most wheel-based robots, stairways are an insuperable obstacle. The width of doorways, the space between furniture or missing space to turn around can likewise limit robots to access a desired place. The height of desks, cupboards or switches needs to match the robot's ability to move and stretch in order to enable interaction. As vision-based recognition systems perform worse in recognizing objects in bad lightning conditions, the installation of additional light sources could produce relief.

Important for humans are the following factors in the design of an intelligent environment:

Comfort. Living spaces and work places should assist human users by offering a practical environment, i.e. all needed objects in a certain situation are placed within reach, the furnishings and facilities fit the specific needs, etc. For additional comfort, context-aware services and proactive functionality simplify repeating tasks and remove complexity. Technical systems should take over activities according to their strengths (see Sec. 4.1.1), such as routine tasks, simple control actions like switching on the light on activity, but leave complex or creative tasks to humans.

Optionality of Technical Systems. Technical systems should not entirely replace conventional ways of task completion, following the principle of 'augmentation instead of automation'. Proactive behavior of an intelligent home should not manifest in patronizing inhabitants, but rather in offers and suggestions they can adopt or silently ignore. The ability to override the system's 'intelligence' needs to be given at every time.

Well-being and Style. People want to feel comfortable in their environment, recognizable by the amounts of money spent for attractiveness and design. Besides functionality, the emotional relationship to objects and the so-called 'visceral design' (Norman, 2003) become increasingly important. A chair is no longer an object for comfortable sitting but sometimes a piece of art. A similar trend is observable in electronics, with regard to thoroughly and artistically designed phones, computers or home entertainment components, using expensive materials like glass and aluminum. Environments designed for machines and humans cannot neglect this requirement any more. Although being suitable for robot use, such environments need to satisfy the human wishes of a pleasurable, nicely designed home.

5 CONCLUSIONS

We have presented an approach for supporting robotic systems in interaction with physical objects by *Cognitive Objects*, with which we have opened a completely new research field at the intersection of pervasive computing and personal robotics. *Cognitive Objects* are real-world artifacts embodied in an interaction that include sensors, actuators, communication, and computation, cooperating with humans and robots to support task execution. Today's robotic vision systems, and overall interaction capabilities, are not sufficient for arbitrary object recognition, hindering a full integration of personal robotics in real-world environments. By cooperatively disclosing information about themselves, *Cognitive Objects* facilitate the recognition of and interaction with any kind of object by robots and thus are a step towards more comprehensive robot-object interaction. At the same time, *Cognitive Objects* are not singularly designed for machine-machine interaction, but remain equally usable by humans, maintaining usability and affordances.

We demonstrated the potential for shared object usage by humans and robots in our *Cognitive Office*, an intelligent environment using a robotic middleware, and showed the potential for supporting mobile interaction, context and location awareness.

We have given initial recommendations for the design of objects and environments with regard to a shared usage by robots and humans. *Cognitive Objects* can sustainably support and stimulate research in personal and robot interaction, as well as ubiquitous computing, as they provide valuable ground truth data to robots and facilitate interaction for both humans and robots. In the future, we plan to integrate further *Cognitive Objects* into our intelligent environment, focusing on supporting ambient assisted living and personal robotics scenarios and their evaluation in complex interactions.

Resources. Source code, documentation and data sets of the presented systems and environment are shared via https://vmi.lmt.ei.tum.de/ros/.

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