Visualization of Robot's Awareness and Perception

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ABSTRACT

Today, direct interaction between humans and robots is limited, although the combination of human flexibility and robots power enables a growing productivity. The problem for humans lies in the nearly unpredictable behavior and motion of the robot itself. However, we can enhance human's view with more information to get knowledge about robot's perception and awareness. We use Augmented Reality methods for providing the information in an adaptable visualization for different user types. We show that our approach leads to shorter development cycles as well as to safer human-robot interaction.

Categories and Subject Descriptors

C.2.4 [**Distributed Systems**]: Distributed applications; D.2.11 [**Software Architectures**]: Middleware; D.2.12 [**Interoperability**]: Data mapping, Distributed objects; H.5.2 [**User Interfaces**]: Prototyping, Interaction styles; I.3.6 [**Methodology and Techniques**]: Device independence, Interaction techniques

General Terms

Design, Experimentation, Measurement

Keywords

Augmented Reality, Visualization, Robot Awareness, Robot Perception, Development Framework, Middleware, Publish/Subscribe, Embedded Devices

1. INTRODUCTION

Today, the operating areas of human workers and robots are strictly separated in most industrial processes (see [4, 5, 8]). The reason for this is the absence of an adequate sensory control leading to a lack of safety and a high risk of injury for humans. However, in a flexible production process it would be highly desirable to support a direct interaction between a robot and a person. In case of such an overlapping operating area, the person has to be detected reliably (no false negatives are allowed) and the robot's movements have to be planned and adapted dynamically according to that position as well as to all positions that this person will reach in the near future [14]. The detection of humans is based on movement, hand, torso, and face detection with cameras (e.g., SafetyEye [2] or QuadCam [1]), but also laser scanners and other sensors are used [29]. The main disadvantage of all these systems is that it is almost impossible to guarantee full detection and thus, the industrial exploitation of such systems is currently limited.

In case of cooperation it is strictly necessary that the robot interprets all commands correctly and executes them reliably. In an automated production process, commands are often given via control panels, but in advanced interaction scenarios a robot has to understand voice commands [12] or even gestures [7]. What additionally complicates interaction is the fact that the sequential execution of a pre-programmed action as known from production lines is not possible any more. On the one hand, the robot needs to react on the fairly unpredictable behavior of persons in its working area. As a consequence, on the other hand, it may generate complex movements that are unexpected for the human operator. Knowing the robot's future intended movements, a person would be able to react adequately and the cooperation process could be improved significantly. This would be a step towards a more efficient cooperation. Currently, direct cooperation between humans and robots in industrial applications is limited to only a few simple scenarios, where the risk of injury is only very small (well known examples are "CoBots" described in [20]).

Because it is intrinsically impossible to foresee every action and movement of a person, and interpret all the respective gestures correctly, it will be very difficult to develop a robot that always behaves according to human expectations. This leads to the opposite approach, making the human collaborator aware of the intended behavior and movements of the robot. This awareness includes of the robot's perception, internal state, and next movements. Just observing this information on a monitor complicates a seamless interaction. Sound signals or verbal output might be a solution but the amount of information is too large and to complex for a human acoustic perception. Most industrial application anyway will not permit easy acoustic communication due to background noise. The large amount of complex data generated by a robot during operation has to be transmitted quickly and presented in an adequate way. We believe that visual techniques are here the most appropriate. This is further supported by the fact that more than 80% of human communication is nonverbal (e.g., through gestures and touch, by body language or posture, by facial expression and eye contact, etc.), see [18]. Therefore, Augmented Reality (AR) turns out to be the technology of choice in such cases. AR is already in use in many different industrial applications, e.g. in manufacturing planning [11], automobile development [13], or training and assistance to maintenance [28], a survey of different projects in automotive and aerospace industry is given in [22].

Using Augmented Reality techniques for visualization the rich set of data from robot's perception has a lot of advantages and enables different views on the robot for different purposes:

- Persons interacting with robots are aware of the robot's intentions, next movements, as well as areas which may be dangerous.
- Engineers can exploit the visualization of sensor data or internal states (e.g., axis positions, torque, current, etc.) to develop and debug robot applications.
- Machine maintenance personnel are able to identify erroneous components quickly or use appropriate visualizations of logging information from the fault recorder for maintenance and repair purposes.

This list of examples can be extended. Although we consider all the aspects listed above, we mainly exploit the techniques in the role of an engineer in our lab. We primarily benefit in getting a better understanding of the complicated relation between a robot as a complex actuator system and its environmental perception through a heterogeneous sensor system.

To put such an AR approach to work we face many challenges on the technical and the system side. This is because a real robot application is composed from distributed heterogeneous hardware and software components that are interconnected via field-buses. Because we assume that the robots may be mobile, wireless communication links have also to be included. Additionally, components may be removed or added. Particularly in an experimental setting as we have it at the moment, dynamic changes should be easy. Therefore, our approach of obtaining the needed information for presenting it in an AR application focuses on a high degree of flexibility and adaptability.

First, we developed MOSAIC, a generic abstraction for all sensor and actuator components with a unified data interpretation. It supports a convenient way for sensor data processing in distributed applications providing an adequate programming model. In particular MOSAIC allows the interoperation between real and virtual sensors and actuators because of a single powerful model. The sensor model of MOSAIC also considers a wide range of typical faults in such applications.

As a second important prerequisite for the seamless interaction and the integration of real and simulated components in an AR scenario we developed FAMOUSO, a communication infrastructure that offers an easy to use interface. FAMOUSO hides the heterogeneity of the systems as well as networks. It is the basis for any interoperation throughout the distributed system. FAMOUSO can be installed on

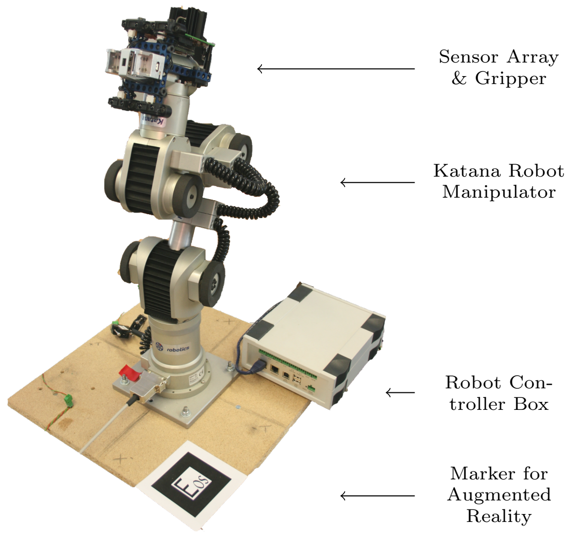


Figure 1: Katana Manipulator

powerful workstations down to simple 8-bit controllers and supports the idea of a system composed of smart sensors and actuators.

The main contribution of our paper is to show, how these system components support the visualization in a robot application. We start with a description of an experimental scenario that motivates our technology and also shows the way the robot is visualized. Subsequently we introduce MOSAIC followed by a brief description of FAMOUSO. Afterwards, we discuss the visualization of the sensor and actuator information and describe different views to the robot. A summary concludes the paper and gives an outlook on further research.

2. SCENARIO DESCRIPTION

Large industrial plants are difficult to handle in lab environments, and from conceptional point of view, evaluating of our approach, a scaled/similar scenario is even possible. Our scenario setup "simulates" the mentioned interaction of an industrial robot with human workers and developers. For a realistic representation we chose a light weight manipulator equipped with a number of virtual and real sensors, a visualization component, and at least a human, interacting with the scene. The setup contains different hardware and different network types, and for the interaction and data interpretation a combined stacked architecture with MOSAIC and FAMOUSO is used, which we describe briefly in Section 3.

Robot

The "Katana" robot [19], illustrated in Fig. 1, has five degrees of freedom with a concurrent velocity on all axes of 90° per second. The robot manipulator is controlled by a PowerPC that receives movement commands from the path calculation component located in another sub-network as depicted in Fig. 2. The control unit transmits its current state, and we enhance the robot control mechanisms by providing distance measurements of real and virtual sensors from outside, because the robot itself has no sensors for environmental perception.

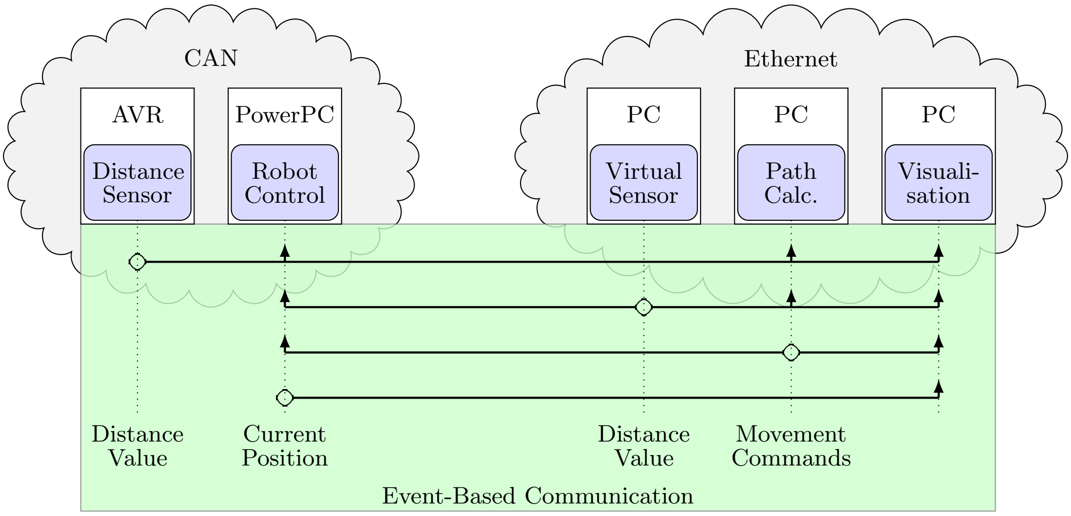


Figure 2: Scenario structure and information exchange

Sensors

We mounted an array of infrared distance sensors close to the tool center point of the robot. The sensors are connected to an 8-bit Atmel AVR micro-controller that publishes the measured distance values, to allow other participating components to work on the values. As shown in Fig. 1, the sensor array monitors the environment of the part, which can be moved with the highest velocity and highest potential risk for damage and injury.

Furthermore, for the development of such complex systems the integration of simulated/virtual sensors represents a helpful possibility for design and validation. Virtual sensors provide the most flexibility, because they can be freely modeled and placed at every point the developer wishes. This offers scenarios where the variability of virtual sensors can be used to model virtual walls.

Virtual or simulated sensor signals are generated on a PC, and we use our experiences in integrating virtual components into real world applications [26] to apply also an infrared sensor as an additional distance sensor at the tool center point of the manipulator, looking in the opposite direction of the real one.

Again, the combination of MOSAIC and FAMOUSO hides the nature and the characteristics of the sensor in general, thus nodes that work on sensor values are not able to distinguish the origin.

Visualization

The visualization component displays continuously captured camera pictures enhanced with augmented reality for showing additional information, as depicted in Fig. 3. It is realized on a separate PC, but could be also integrated into a head mounted display. This component gets all information, with the help of FAMOUSO, like axis positions, sensor measurements, path calculation, etc. The visualization is highly adaptive and allows customizing in dependence to varying user expectations.

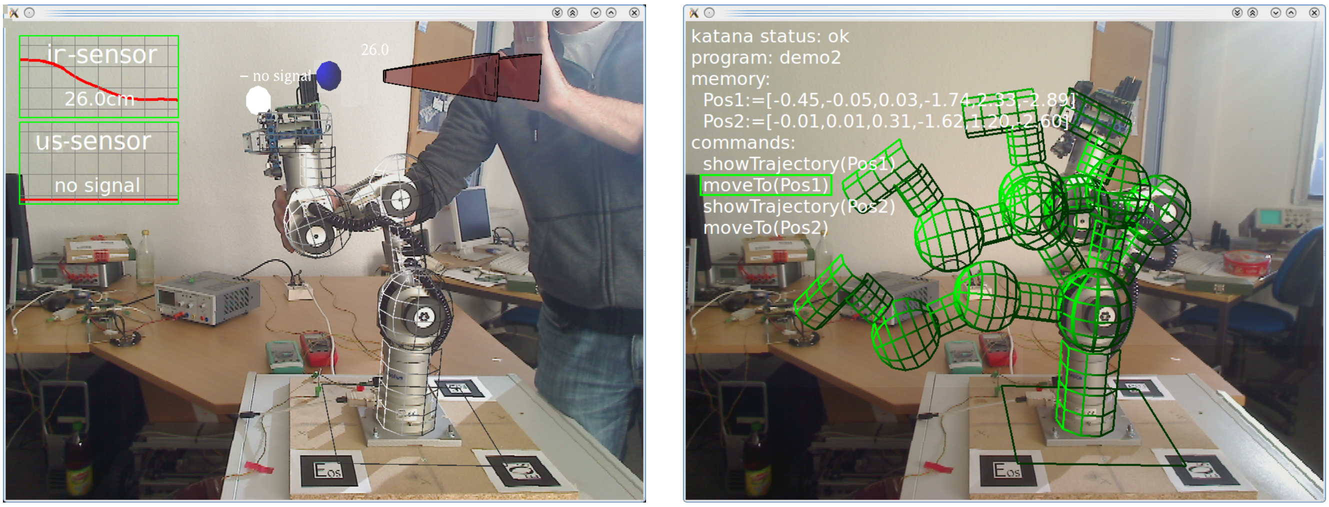
For enriching the captured camera picture with additional information, we use ARToolKit [3], which is an open-source software library for building Augmented Reality applications with the help of markers. The markers are visible on the ground plane of the robot in Fig. 3 and 1, and we use the marker and their known position to draw information perspectively correct. Currently, we provide the following types of augmented reality elements:

1. 3D wire-frame of the robot manipulator
2. sensor position, state, and measurement beam
3. scope diagrams of measurements
4. textual information

We produced a geometric model of the manipulator. The base is placed at the base position of the real manipulator to ensure the same origin for all movements. For adjusting all parts of the wire-frame model to cover the real robot, we use the values received from the manipulator control unit. To enable humans to foresee next movements of the manipulator, the visualization interprets the movement commands of the path calculation and draws additional wire-frames approximating the trajectory.

The second point, the sensor representation consists of three parts: sensor position, sensor state, and measurement beam. The position and beam characteristic/geometry is determined from an electronic data sheet. At the position of the sensor a colored sphere is drawn and above the latest state. The beam appearance is calculated from the received real values and drawn accordingly. The data sheet describes the update rate of sensor values too, which is exploited for detecting overdue data. If sensor data are delayed or get lost, the visualization shows that information by changing sphere color at the sensor position to white, meaning a white hole or there is a perception gap. As mentioned, we integrated a virtual sensor, and in Fig. 3(a) it is visualized by a white circle, because it was not available at the moment as the picture was taken, which is also indicated by the "no signal" notification text above the white circle and in the according diagram.

The next visual element is a parameterizable scope diagram. It shows received values, typically sensor measurements, over time and enables to get an overview about the history of values maybe of the last 10 seconds.



(a) Visualization for engineers, presenting the current measurement of the two sensors

(b) Visualization for workers/developers, illustrating the future movements of the manipulator

Figure 3: Multi-modal visualization of awareness and perception of a robot manipulator

The last supported type of visual element is plain textual information, which usually is used to present status information. In our scenario, we display information about current robot states, following movement parameter and future command lines.

The visualization combines the features of ARToolKit, MOSAIC and FAMOUSO to be adaptive in general and show the observed system in dependence of the current context always.

3. ARCHITECTURES

In the section before we describe a scenario that combines a heterogeneous hardware, different network types, and an intensive data exchange in a distributed application. With the combination of FAMOUSO and MOSAIC we integrate two types of a middleware to facilitate the development, debugging, production process, and maintenance. FAMOUSO, the communication middleware handles the transmission of all information transparently for applications. The second abstraction has to handle the different sensors and sensor values. Hence, MOSAIC is responsible for adequate filtering, selection, fusion, and validation of the processed information in a common programming abstraction.

3.1 Sensoric – MOSAIC

We developed the MOSAIC (fraMework for fault-tOlerant Sensor dAta processIng in dynamiC environments) framework that provides an appropriate programming abstraction – the "Abstract Sensor" – for distributed environments. The Abstract Sensor combines the ideas of the hardware oriented concept of "Smart Sensors" from Breckridge and Katzberg [10], the modular structure of "Logical Sensors" from Henderson and Shilerat [15] enhanced by the fault-tolerance approaches from Marzullo [17].

Abstract Sensors were developed as a common programming model for distributed applications. It provides a general interface and structure for the four types: The first one, a Smart Sensor uses a real transducer to obtain perceptions of the environment. The measurements are preprocessed and validated in a structured way described in [32]. Afterwards, the results are transmitted. The second, the Fusion Node does not include any real measurements, but instead it merges values of different sensors to one result with a higher validity. The third variant is the virtual sensor that generates ideal or faulty measurement, helpful for developing and debugging purposes. The fourth type of an Abstract Sensor interacts directly via an actuator with the environment. Usually, it receives messages that contain information for steering the actuator. In our scenario all types of an Abstract Sensor are used.

In distributed scenarios a correct identification, interpretation, and an adequate processing of transmitted data is needed. MOSAIC includes the idea of CODES [21], which describes the communication characteristics of node all information that are necessary to interpret events correctly within an electronic data sheet. This description and the common communication interface enable MOSAIC to cope with a dynamic variation of number and types of available sensors.

Fault-tolerance mechanisms in a programming abstraction for distributed applications have to be in focus of the attention, due to the increasing fault probability in such systems. Faults occur in the measurement process, during processing, and communication, as well as in actuator context. Resulting from the distributed approach, a central fault detection and isolation unit is impossible. We enhance existing programming abstractions by fault detection mechanisms in order to be aware of faults as close as possible to its origin. Therefore we analyze the faults of a sensor - processing - communication - processing - actuator chain, discuss possible detection methods, and integrate them into the common structure of an Abstract Sensor.

The concept of an Abstract Sensor including a common communication interface requires a communication middleware that encapsulates the heterogeneity of underlying networks and hardware.

3.2 Communication – FAMOUSO

Our Middleware FAMOUSO (Family of Adaptive Middleware for autonomOUs Sentient Objects [16, 24, 25, 27]) provides an event-based communication over different network types, according to the publish/subscribe paradigm. In contrast to the usual address-based communication, an anonymous content-based communication is used, where events are exchanged between communication end-points. Publisher as well as subscriber are rolls that applications have during the communication. Related to its characteristic as publisher, subscriber, or both, applications specify the kind of events they produce or consume. On that simple scheme, FAMOUSO provides spontaneous and dynamic many-to-many communication without implicit assumptions about synchrony of events. The communication is always asynchronous, and avoids control flow dependencies, enabling the autonomy of communication participants.

FAMOUSO runs on a broad variety of different hardware platforms ranging from low-end 8-bit micro-controllers up to high-end 64-bit server systems and enables interaction over different communication media like the CAN [23] field bus, Wireless Sensor Networks (WSN) like 802.15.4 [31], Wireless Mesh Networks like AWDS [6], and Ethernet like UDP broad- and multicast. FAMOUSO can be used from different programming languages (C/C++, Python, Java, .NET) as well as from engineering tools (Labview, Matlab/Simulink) simultaneously. FAMOUSO ensures seamless information exchange between the different system environments, allowing the user to concentrate on the main development task and avoids deflecting the user with underlying low level system concerns. Thus, the middleware enables the developers to individually choose their preferred combination of tools and languages. Objectives of FAMOUSO are configurability, adaptability, portability, and efficient resource usage to allow also the deployment on small resource-constrained embedded devices.

4. BENEFITS OF VISUALIZATION

Section 2 described a human-robot cooperation scenario. Now, we discuss how Augmented Reality can help to understand a robot's environmental perception as well as its awareness. We study different views and discuss advantages and show how they are useful for different types of users.

In the following we describe and discuss firstly different views for developers, and secondly do the same for the workmen.

4.1 Different Views for Developers

Engineers and maintenance technicians require a wide bandwidth of complex information over the development and deployment cycle of a robot. The intuitive representation of sensor data and system states in combination with the robot should help to get a better understanding of complex relations between a robot and its perception of the environment and therefore simplify the development and debugging. We discuss two directions of the enriched visualization, the first one is oriented to the perception of the environment and the second one to robot's awareness and internal states.

Perception

The engineer examines the behavior of the real sensor in Fig. 3(a). On the left side a diagrams with the current measurements are visible for this purpose as well as the measurement beam of the sensor that gives an impression of the range observed by the infrared sensor. Furthermore, exploiting the flexible expandability of our scenario structure, the engineer is able to integrate additional participants that record for example the history of all measurements of a certain sensor and calculate some statistics etc. As mentioned in the scenario description an additional virtual infrared sensor was positioned into our scenario. The application developer can use this adaptive tool to validate the configuration of the sensor infrastructure. By varying the parameter of the virtual sensor beam, variance, range, position, etc. the developer can determine an optimal coverage of the environment monitoring or test the fusion algorithm of the distance measurements.

Awareness

The second mode of our visualization integrates the internal awareness of the robot. That could be states related to actuators and sensors, or current calculations of the path, etc. In complex scenarios these insights are extremely useful to validate path planning algorithms, fusion processes or fault detection algorithms. The fault detection capability was examined by the time of capturing the picture presented in Fig. 3(a). The virtual ultra-sonic sensor does not work correctly marked by the left white sphere and the "no signal" notification above. Probably the virtual sensor was switched off, generated wrong measurements, or lost its network connection in this situation. Hence, the developer uses the virtual sensor to validate the reaction of the whole system to sensor faults.

For development purposes both modes can be superimposed. To handle the large number of information and their complexity the concept of a "magic lens" can be adapted [9, 30]. For example, an additional marker moved by the developer into the augmented scene activates a specialized presentation of the information. This enables further nice features like zooming functions or different layers by adapting the visualization.

4.2 Different Views for Workers

In a production process the information embedded in the Augmented Reality should be perceived very fast during the workflow. To avoid an overload of the human perception, a careful selection of the visualized information is necessary. Moreover, the hands of a worker are tied by tools and work pieces, and adapting the visualization by gestures, etc. is not possible.

Perception

Usually, in production processes it is not necessary to whelm the worker with detailed information about the perception of the robot, because the visualization of these information would overload the display and are not really helpful to foster an easy cooperation.

Awareness

In contrast to the perception, the awareness of future steps in the robot's workflow is more important. Fig. 3(b) shows a visualization for a human worker interacting with the robot. The worker can fast perceive robot's current position, as well as the trajectory of the robot in the near future. Additional, we provide state information and current commands but we use low contrast colors to avoid the deflection of workers attention from the most important information. Even that reduced visualization provides an important and intuitive help. A worker gets aware of robot's doings and potential dangers. The occurrence of unexpected robot behavior can be realized before the robot starts this. In combination with a reliable environment monitoring and adaptive path control, the risk of accidents can be minimized significantly.

5. CONCLUSION

It is not possible for a machine to understand human intentions and furthermore to react in an appropriate way so that every risk of injury for humans can be ruled out. The robot can only interpret its perception of the human body, but it has no possibility to look into human's mind to obtain current aims causing a special motion of an arm, for example. In contrast, the visualization of robot's awareness and perception with the techniques of Augmented Reality provides access to the intention behind current and future robot behavior. This knowledge enables the user to get a temporal advance in cooperation with robots. Our approach is a step towards human-machine-cooperation in complex scenarios. The multi-level visualization improves the cooperation in different situations: workers interact safer with a robot manipulator and engineers are able to monitor complex relations for a faster development process.

The scalable and adaptable visualization requires a general availability of all relevant data with no regard to localization, underling networks or hardware configurations. In this paper we describe briefly our stacked architecture framework including the event-based communication middleware FAMOUSO and the programming abstraction MOSAIC for this purpose.

These technologies can be utilized in the future to develop robot applications that will solve more complex tasks with a higher reliability and a lower risk for human workers than today's robotic applications do.

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