RRLAB
The Robotics Research Lab

Summary and Examples in Application

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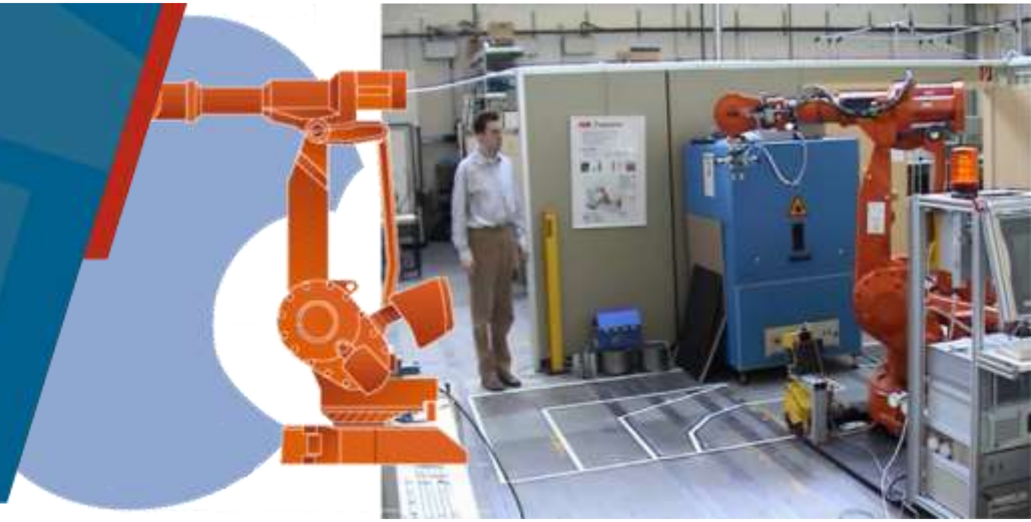
Content

- Application: „human centered automation“
- Robot systems, hardware and communication systems
- Control concepts
- Test results
  - Quantitative results regarding reaction times of the system
  - Optimization of the system
  - General computation of safety areas
- Summary of the lecture

Setup of a Dynamic and Flexible Safety Area for Robots



Basierend auf der
Diplomarbeit
von **Roland Krieger**

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The "Human Centered Automation"

- Previously: Division of workspace of humans and machines
  - Human only as observer (surveillance, maintenance, …)
- Future: Cooperation, use synergies
  - Speed, force, accuracy and media resistance of robots
  - Sensory abilities, knowledge and dexterity of humans
- Human-robot-cooperation is a (relatively) young research area (first publication 1992 by Y. Nakauchi: „Multi-Agent Interface Architecture for Human-Robot Cooperation")
- Fraunhofer Institute (IPA) coined term „Humanzentrierte Automatisierung"/"Human Centered Automation"

Problem Description and Goal Description

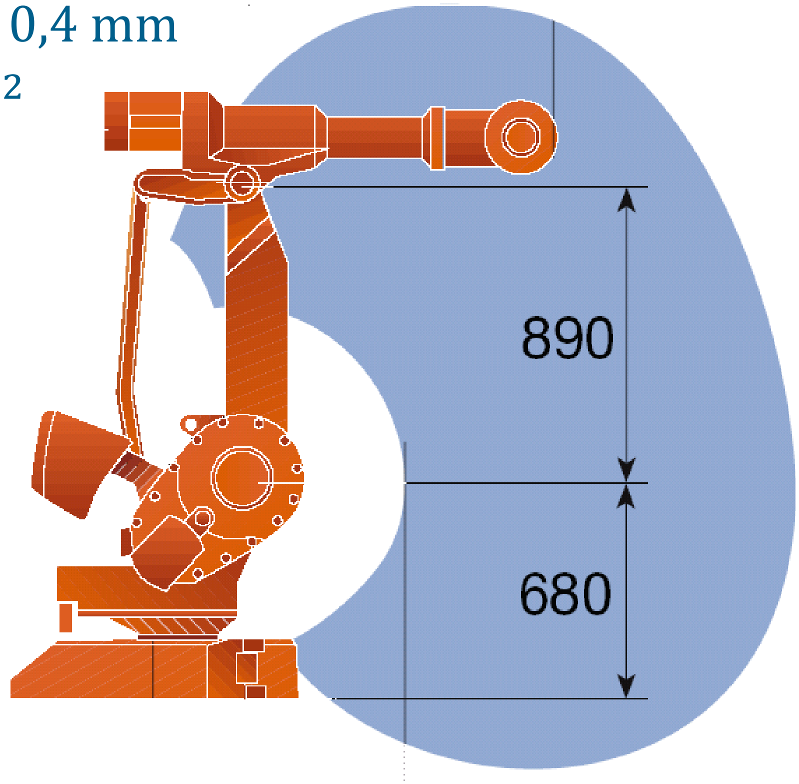
- Problem: Industry robots are „blind“ to their environment
  - Usually only internal sensors
  - Often only binary detection (workspace free/occupied)
- Goal: Setup of a dynamic and flexible safety area
  - Different safety areas which trigger different actions: emergency stop, slowing down, or acoustic signal
  - Detection of humans with fusion of different sensors, with different physical measurements: Ultra sonic, laser scanner, light barrier, contact mat, radar etc.
- Adaptive trajectory control which considers the current obstacle map
- Future goal: Interaction between robot and human

Surveillance of Safety Area

- Possibilities
  - Surveillance of robot arm
    (one point-, multi point-, or surveillance of complete arm)
  - Surveillance of work space
- Static or dynamic surveillance
  - Thigh cooperation with human is desired
  - Flexible reactions to different situations
  - Therefore static surveillance (determined before program start) not suitable

Robot System: ABB IRB4400

- Maximal range: 1,96m
- Maximal load: 45 kg
- Position accuracy: $0{,}07 - 0{,}1 \text{ mm}$
- Precision: $0{,}25 - 0{,}4 \text{ mm}$
- Maximal TCP acceleration: 14 m/s^2



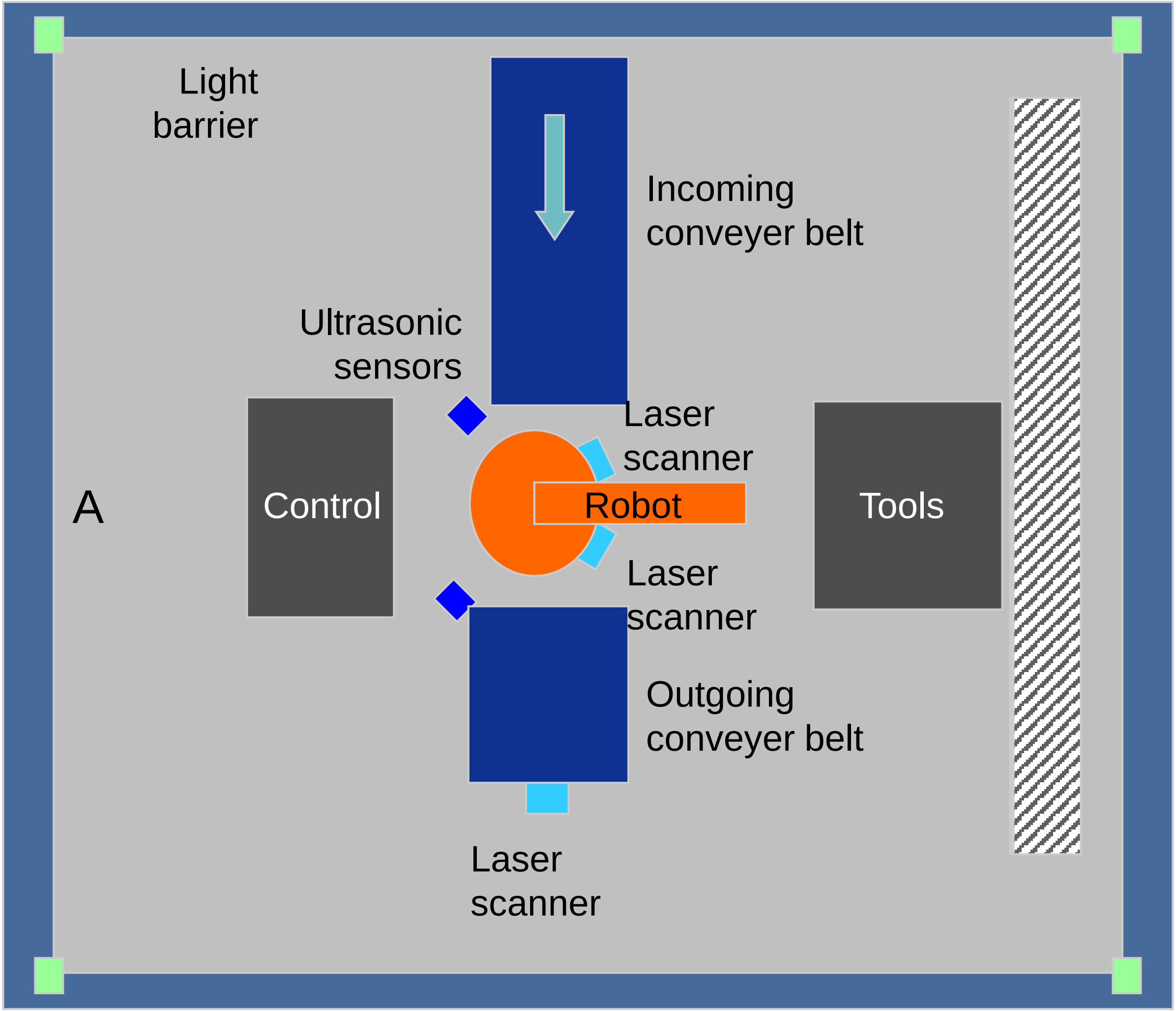
Control Hardware: Safety-SPS PSS3000

- Multi-channel, redundant setup
- Integrates test and safety algorithm
- Fulfills requirements of $\mathrm{EN}\ 954-1, 11/94$ up to category 4
- Data memory: $234\ \mathrm{KByte}$, program memory: $1024\ \mathrm{KByte}$

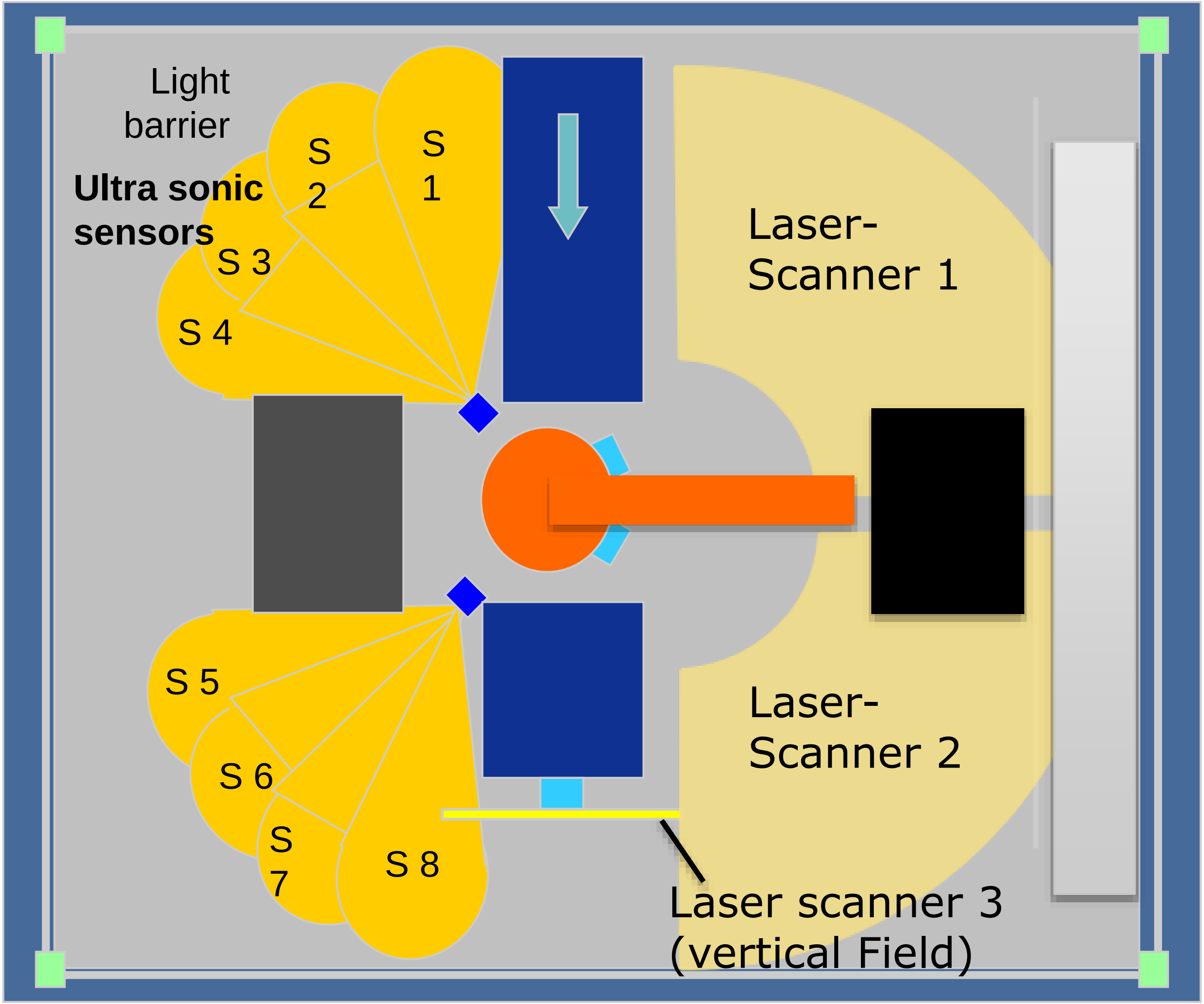
Sensors

- Laser scanner
  - Established in automation, widely accepted in industry
  - Covers big safety areas (up to $12\,\mathrm{m}$)
  - Flexible usage (safety-/warning area)
  - Costly
- Ultra sonic sensors
  - Cheap bulk good
  - Extremely interference prone, no certification
- Light barrier
  - In the given application it would be used to reduce the speed of the robot (no emergency stop)
  - Suitable for safety application
  - Proved and tested in industrial applications

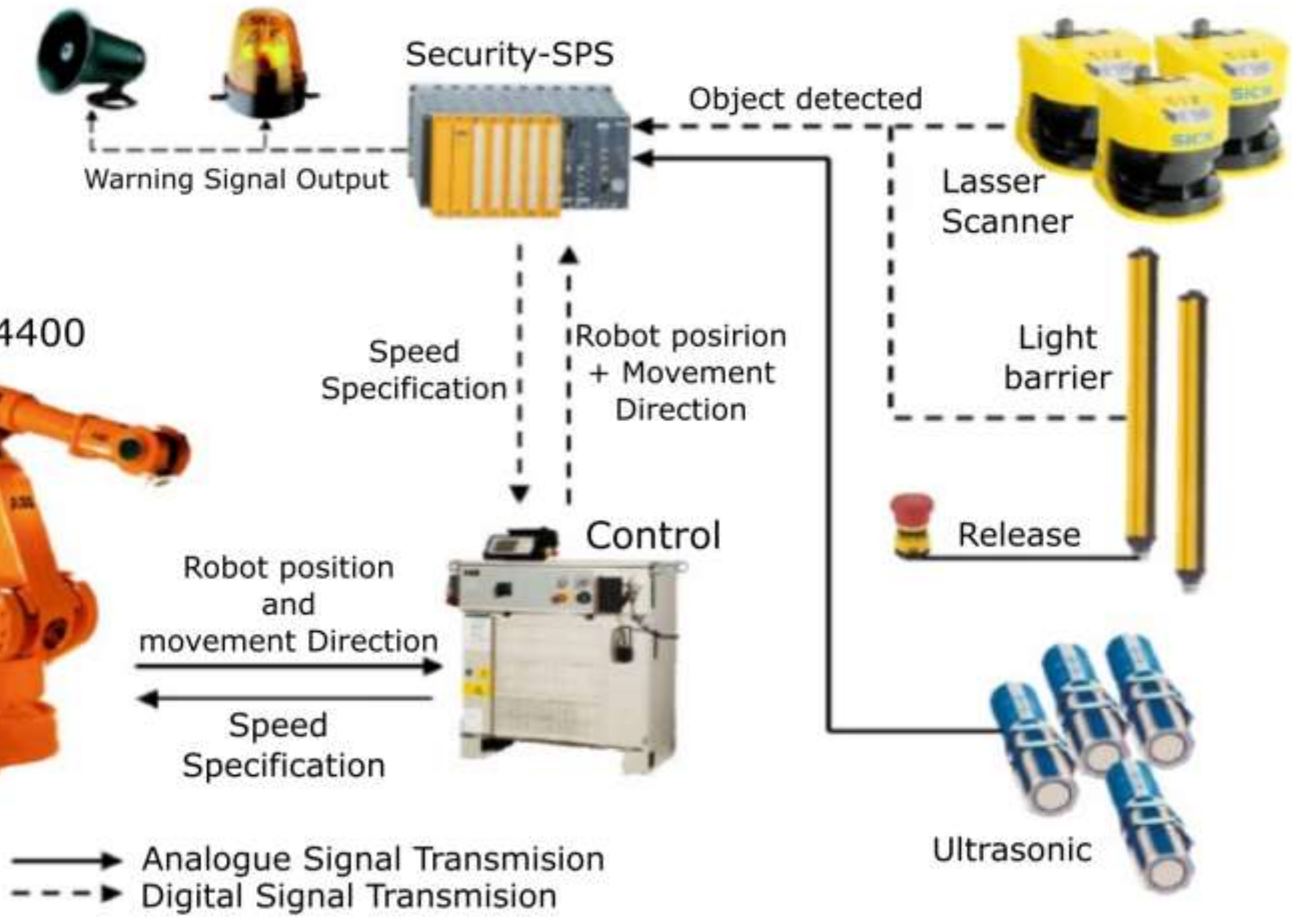
Workspace: System Setup



Workspace: Measurement areas



Communication between System Components



Static Safety Areas with Emergency Breaks

- Analogous to classical robot workspace
- Complete workspace is under static surveillance
- Entering zone 0 interrupts light barrier and triggers the emergency brake
- Pressing a clearance button returns the system into working mode

Static Safety Areas with Emergency Breaks and Warning Areas

- Emergency break area is surrounded by additional warning area
- Interrupting the light barrier reduces robot speed
- Breaching zone 0 ignites a signal light
- Breaching zone 1 stops the robot
- System automatically starts again if the breach is void
- Pressing a clearance button returns system to normal speed and turns off the signal lights

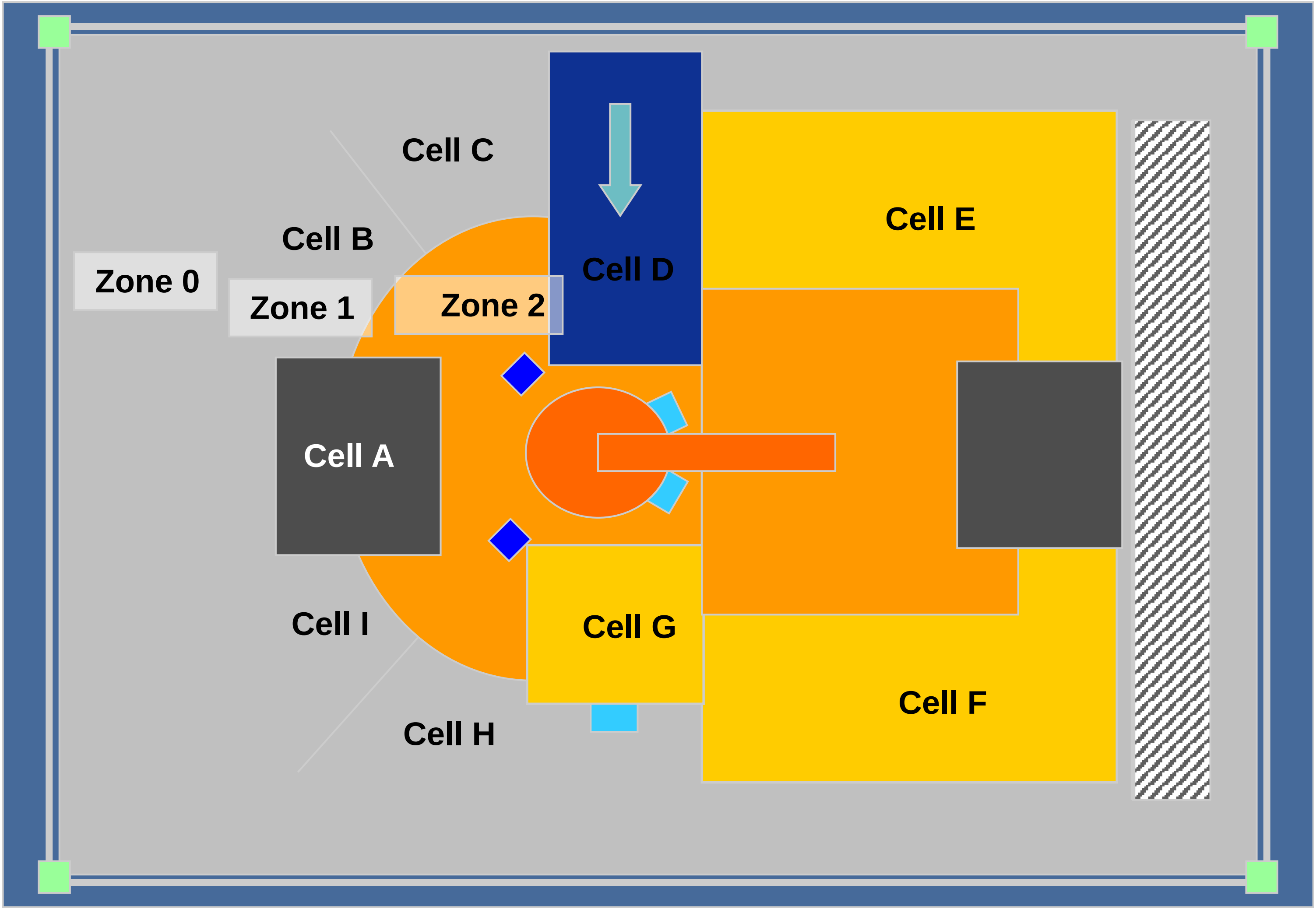
Dynamic Safety Areas

- Speed adjustments and emergency break
- Three gradual safety areas. Depending on the robot position a breaching results in …
  - No reaction
  - Speed reduction
  - Emergency brake
- Safety area contains …
  - Complete zone 2 and cell X,if the robot is in cell X of the safety zone 1
  - Additional cells $X+1$, if robot is in cell X of zone 1 and executes a movement in the direction of cell $X+1$
- Warning area is made up of both cells of zone 1, which are directly adjunct to the cells of the safety area

Dynamic Safety Areas

- Zone 0 breached: Robot reduces speed, signal light is ignited
- Warning area in zone 1 breached: Acoustic signal
- Safety area in zone 1 breached: Stopping of the robot
- Zone 2 breached: Stopping of the robot
- Safety breach is void: System starts again
- Pressing a clearance button: Systems returns to normal speed and signal light turns off

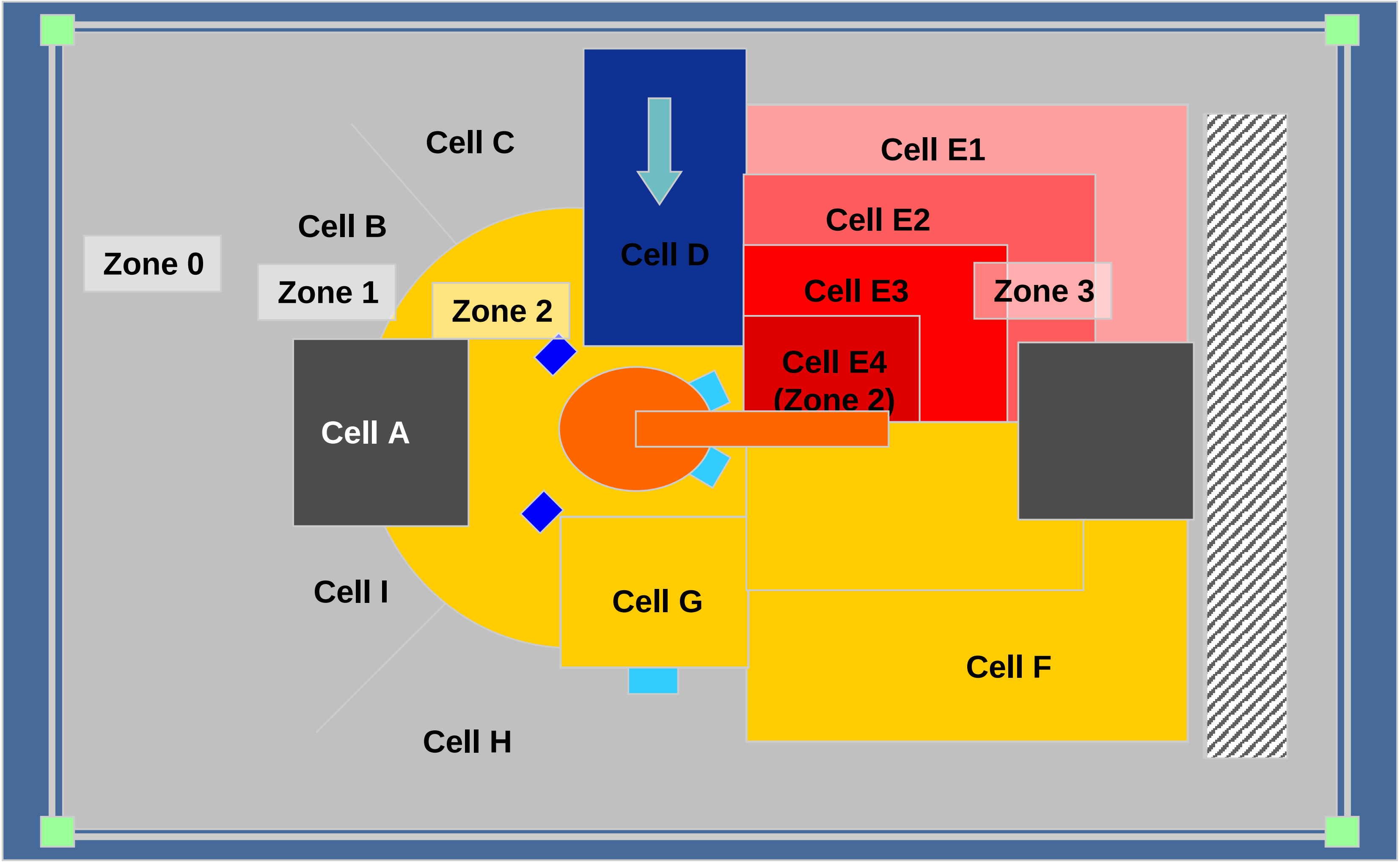
Work Space: Safety Areas



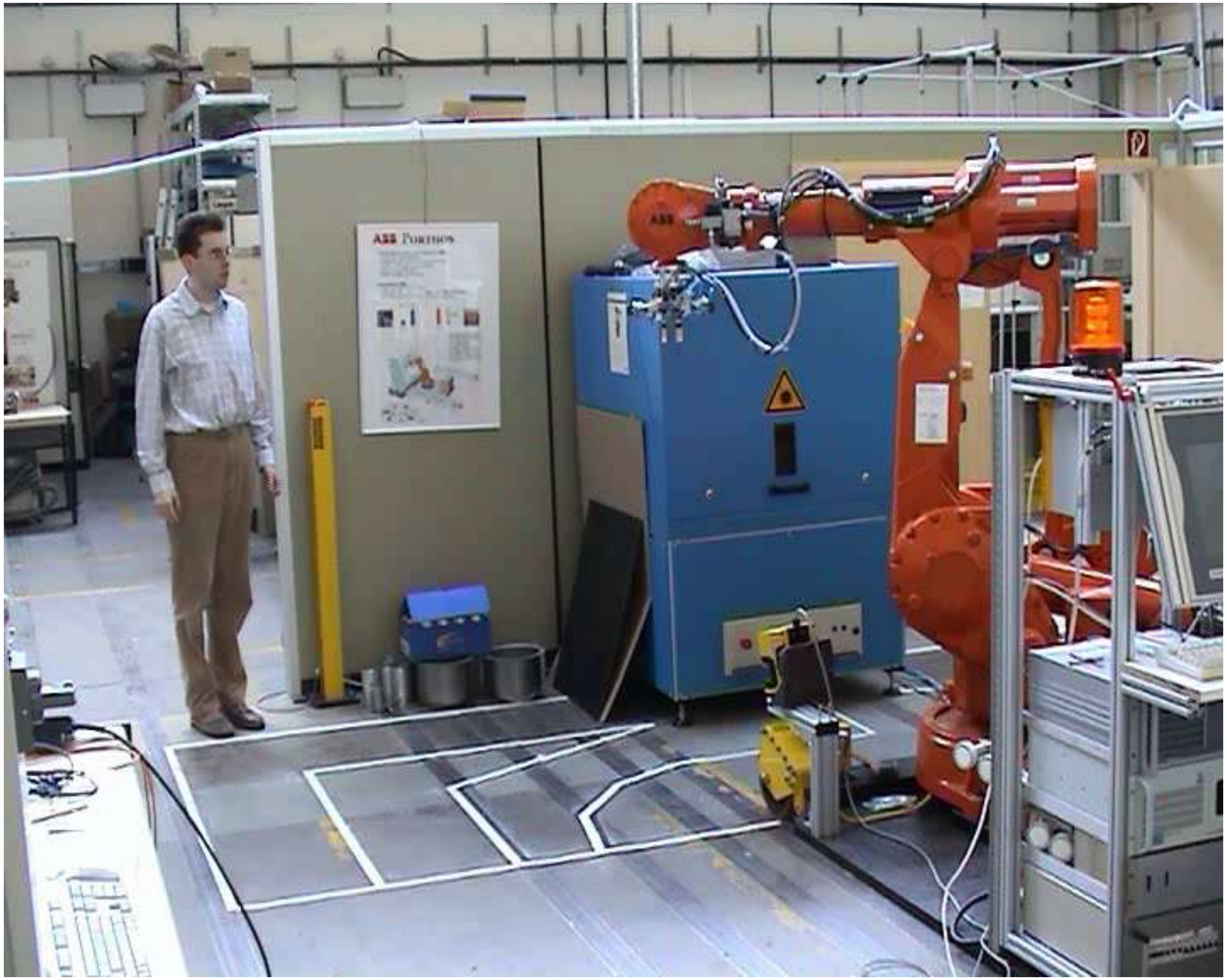
Realization of an Evasion Movement

- Cell E it divided into four sub-cells (zone 3)
  - Requires additional surveillance possibilities
  - Multiplexing of the sub-cells with laser scanner, cyclic surveillance
- Actions if a safety area is breached
  - Zones $0,1,2$: Analogously to previous example
  - Zone 3: Evasion movement (depends on breached cell) instead of breaking

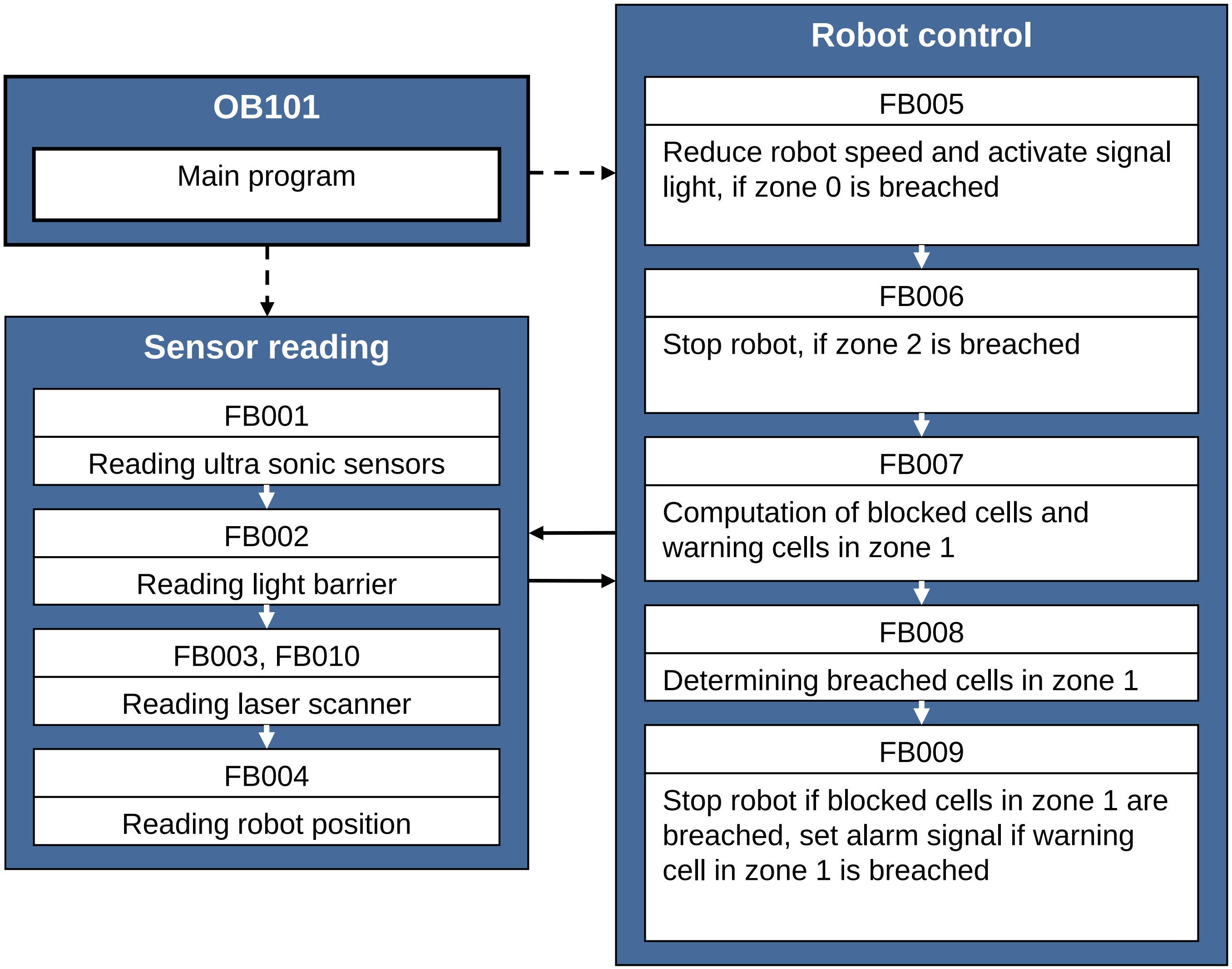
Workspace: Safety Zones



Workspace: Safety Areas



Implementation on the SPS



System Tests

- Software: Bottom-up implementation, black- und white-box tests during the whole development cycle
- Laser scanner, SPS and light barrier: No intensive HW-testing, as the components are certified for safety applications
- Ultra sonic sensors
  - Weak point of the hardware
  - Moderate object detection quality
  - Objects with a highly reflective surface can not be detected reliably (if outgoing sonic waves are not reflected away from the sensor)
  - Objects with a sound absorbing surface are not detected well

Quantitative Results Regarding Reaction Time

Test number	Reaction time laser scanner (ms)	Reaction time SPS (ms)	Reaction time robot control (ms)	Follow-up time (ms)	Sum (ms)
1	120	139	410	221	**890**
2	120	58	405	238	**821**
3	120	215	411	223	**969**
4	120	121	416	113	**770**
5	120	45	415	227	**807**
6	120	124	415	224	**883**
7	120	63	419	229	**831**
8	120	177	417	224	**938**
9	120	81	414	236	**851**
10	120	97	422	218	**857**
Minimum	120	45	405	113	**770**
Maximum	120	215	422	238	**969**
Median	**120**	**109**	**415**	**224**	**854**
Average	120	112	414,4	215,3	**861,7**
Avg. deviation	0	43,2	3,52	20,46	**46,64**

Quantitative Results

- Total follow-up time of the system is on average $862\ \mathrm{ms}$ and $1050\ \mathrm{ms}$ in the worst case
- Reaction/Follow-up times
  - Laser scanners: $120\ \mathrm{ms}$ (worst case $120\ \mathrm{ms}$)
  - SPS: $112\ \mathrm{ms}$ (worst case $270\ \mathrm{ms}$)
  - Robot control: $414\ \mathrm{ms}$ (worst case $422\ \mathrm{ms}$)
  - Robot actuation: $215\ \mathrm{ms}$ (worst case $238\ \mathrm{ms}$)
- Required safety distance $s = 4{,}6\ \mathrm{m}$ in the worst case

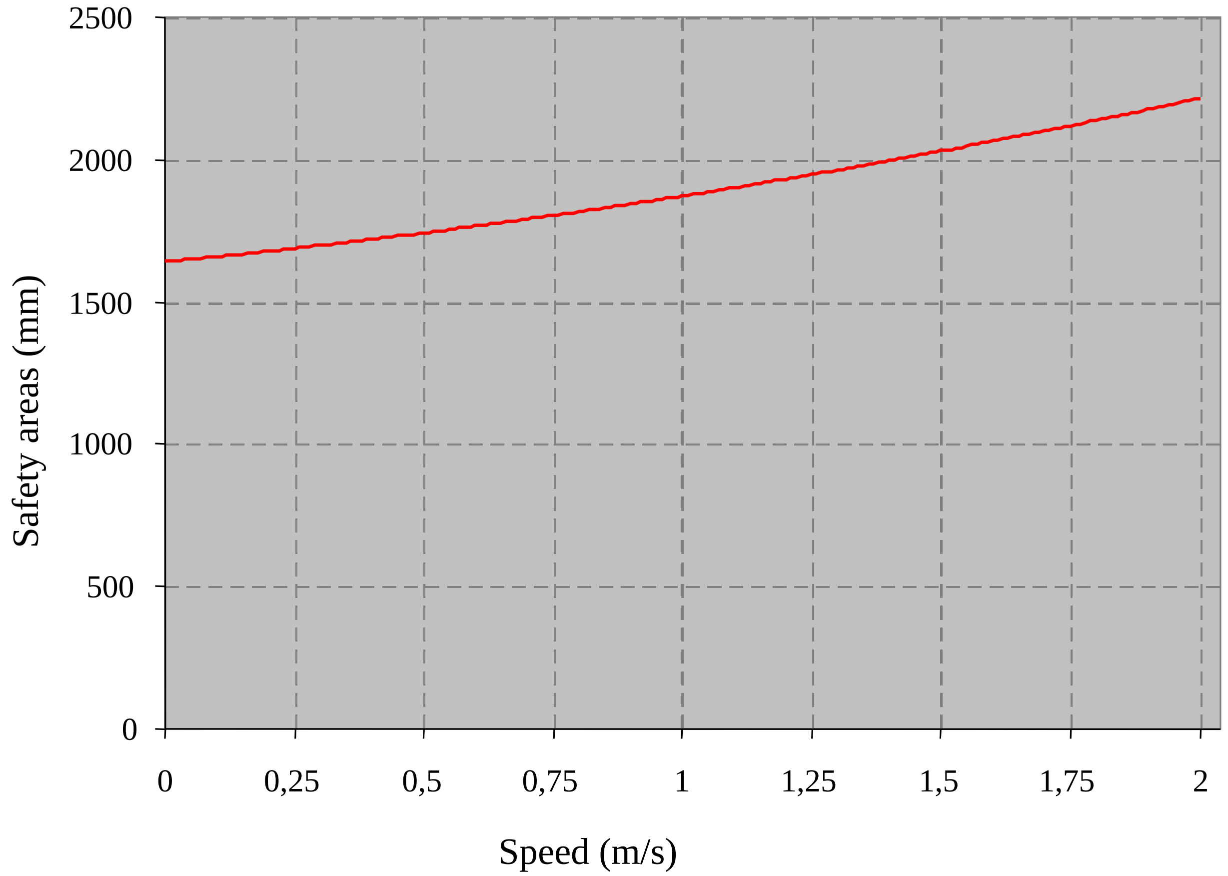
$$s_{safety}(v_{robot}) = t_{total} \cdot v_{human} + t_{reaction} \cdot v_{robot} + s_{follow-up} + s_{minimal\_distance}$$

- $\rightarrow$ Optimization needed

Optimization of the System

- Additional laser scanner prevent switching of zones
  → Reduction by $240\ \mathrm{ms}$
- Direct Control instead of trap routine
  → Reduction by ca. $410\ \mathrm{ms}$
- Optimization
  - Response time reduced to $400\ \mathrm{ms}$
  - Distance reduced to $2{,}2\ \mathrm{m}$

General Calculation of Safety Areas



Summary of the Lecture

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Topics

- Subsystems
- Spatial kinematics
- Robot modeling
- Trajectory control
- End effectors and gripping
- Planning systems
- Control architectures
- Programming of robotic systems

Subsystems and Spatial Kinematics

- Subsystems
  - Mechanic components
  - Joint types
  - Elementary robot configurations
  - Workspace
  - Actuators, sensors, control
- Spatial kinematic
  - Description of objects and object poses in a $3D$ Euclidian space $(E3)$
  - Pose description with 3×3 matrices
  - 6-dim. Description vectors
  - Homogeneous coordinates and transformation matrices
  - Chained pose descriptions

Modeling and Trajectory Control

- Robot modeling
  - Degrees of freedom
  - Geometric model
  - Kinematic model
  - Direct kinematic problem
  - Inverse kinematic problem
  - Dynamic model
- Trajectory control
  - Basics of trajectory control
  - Interpolation types
  - Path planning
  - Spline interpolation

Gripping and Planning Systems

- End effectors and gripping
  - Basics
  - Grip hierarchy
  - Classification of gripping systems
  - Planning of re-gripping operations
  - Scene stability
- Planning systems
  - Basics of robot planning
  - Planning types
  - Planning via searching
  - Cranfield-montage benchmark

Control Architectures and Programming

- Control architectures
  - Basic abilities
  - Schematic visualization of the 4 basic architectures
  - Hierarchical deliberative/function based architectures
  - Distributed deliberative/function based architectures
  - Hierarchical reactive/behavior based architectures
  - Distributed reactive/behavior based architectures
- Programming
  - Programming of industry robots
  - Online-/Offline-methods
  - Types of programming
  - Environment models

Comments about the Lecture

- What was nice/bad?
- Lack of clarity/errors in the content?
- Structure?
- …
- Courses survey:
  (https://vlu.cs.uni-kl.de)

Thank You