Lecture 14: Industrial Robot Safety

March 26, 2026

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Administrivia

- Final project details will be posted on campuswire soon
  - Robot drawing competition!
- Reminder: signup for exam 2 on prairietest
  - Review lecture next Tuesday

Robot Safety

ISO / TS for Robot Safety

- ISO/TS is a *technical specification*
  - A normative document representation technical consensus within an ISO committee
  - This is more than a technical report that is expected to become standard, but not quite a standard
- ISO 10218 outlines robot safety standards for manufacturers and adopters
  - 8/152 pages are dedicated to collaborative operation – a new guidance ISO/TS 15066 focuses on Collaborative Robots

R.N. Shea. "Collaborative Robot Technical Specification ISO/TS 15066 Update." Rockwell Automation, 2016.

Robot Design and Manufacture (ISO 10218-1)

- **Singularity Protection:** The robot must handle "singularities" without creating a hazard
- **Safety-Rated Soft Limits:** Robots must have software-defined boundaries for axis movement and speed
  - Must be as reliable as physical hardware stops
- **Stopping Functions:** Requirements for E-Stops and Protective Stops
- **Pendant Requirements:** Any teach pendant must have a three-position enabling switch
  - If you squeeze it too hard or let go entirely, the robot stops
- **Control Modes:** Clear definitions for operating modes
  - Ex: Automatic (high speed) and Manual/Teach (reduced speed)

Robot Systems and Integration (ISO 10218-2)

The Safeguarding Hierarchy

Elimination/Substitution: Design the hazard out of the cell entirely

Engineering Controls: Use physical barriers, light curtains, or pressure mat

Administrative Controls: Use warning signs, training, and markings

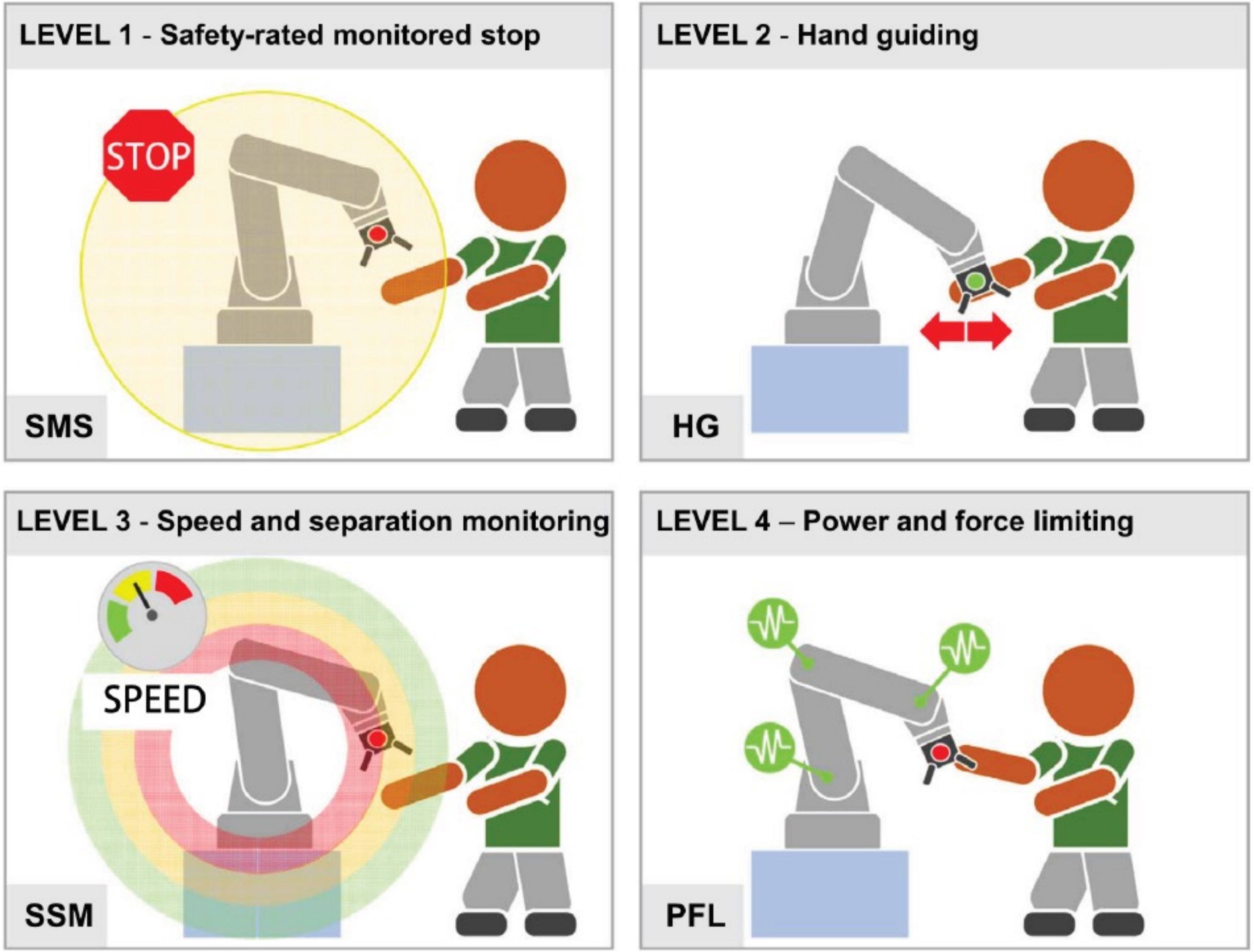
Key Integration Requirements

- **Clearance:** There must be a minimum clearance between the robot’s maximum reach and any fixed structures
- **Spaced Access:** If a human needs to enter a cell, there must be a safe sequence to do so
- **Verification and Validation:** The integrator must test (and document) every safety function

What about Collaborative Robots?

Feature	ISO 10218 (General)	ISO/TS 15066 (Collaborative)
Philosophy	**Separation:** Keep humans away from moving robots	**Interaction:** Allow humans and robots to share space
Main Tool	Fixed structures and engineered controls	Power/force limiting and speed monitoring
Speed	High speeds allowed if guarded	Strictly limited based on proximity and force
Risk Focus	Mechanical failure and intrusion	Human biomechanical limits

ISO/TS 15066:2016 :: Levels



Villani, Valeria, et al. "Survey on human–robot collaboration in industrial settings: Safety, intuitive interfaces and applications." Mechatronics 55 (2018): 248-266.

ISO/TS 15066:2016
Biomechanical Hazard Analysis & Best Practices

Body Region	Max. Quasi-static Force (N)	Max. Transient Force (N)
Skull/Forehead	130 N	260 N
Chest/Sternum	140 N	280 N
Hand/Finger	140 N	280 N
Thigh/Knee	220 N	440 N

- **Eliminate Pinch Points:** Ensure there are no sharp edges, corners, or protrusions on the robot or the end-effector
- **Increase Surface Area:** Padding or rounded surfaces help distribute force over a larger area, reducing the risk of injury
- **Energy Absorption:** Use compliant joints or skins that can absorb energy during an impact

ISO/TS 15066:2016 :: Separation

$$S_p(t_0) = S_h + S_r + S_s + C + Z_d + Z_r$$

$S_p(t_0)$ is protective separation distance

S_h is the operators change in location

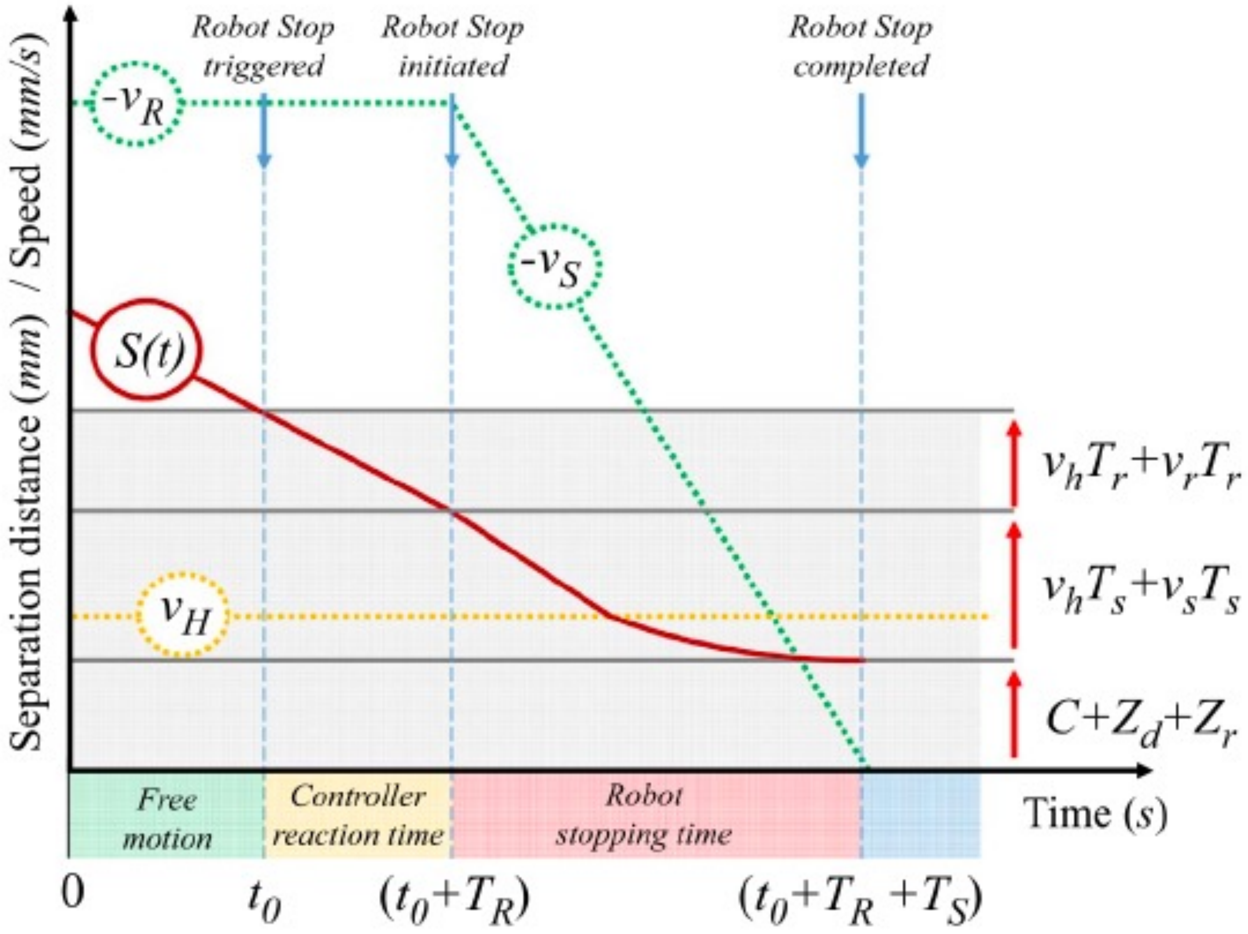
S_r is the robots change in location

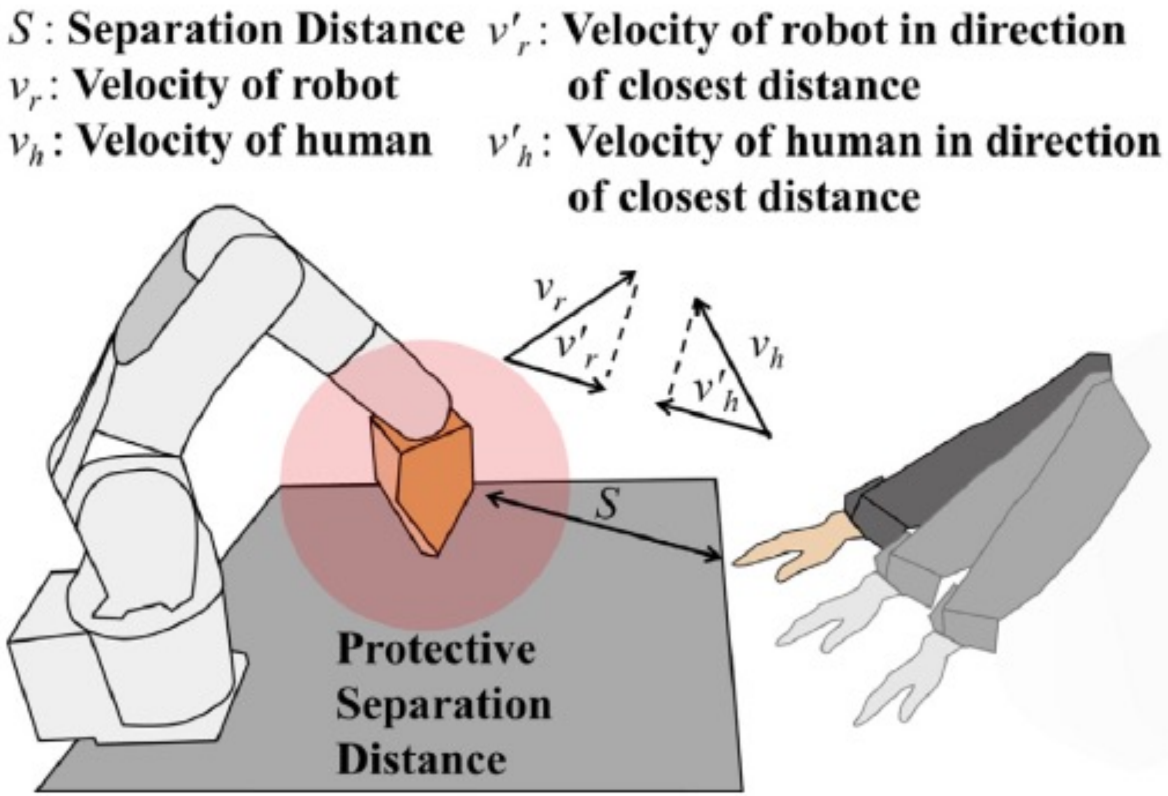
C is intrusion distance of body part that may enter hazard before detection

$Z_d + Z_r$ is position uncertainty for robot and operator

R.N. Shea. "Collaborative Robot Technical Specification ISO/TS 15066 Update." Rockwell Automation, 2016.

ISO/TS 15066:2016 :: Separation



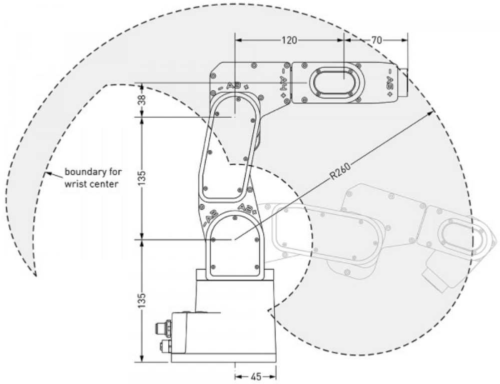


Villani, Valeria, et al. "Survey on human–robot collaboration in industrial settings: Safety, intuitive interfaces and applications." Mechatronics 55 (2018): 248-266.
Kim, Eugene, et al. "Estimating probability of human hand intrusion for speed and separation monitoring using interference theory." Robotics and Computer-Integrated Manufacturing 61 (2020): 101819.

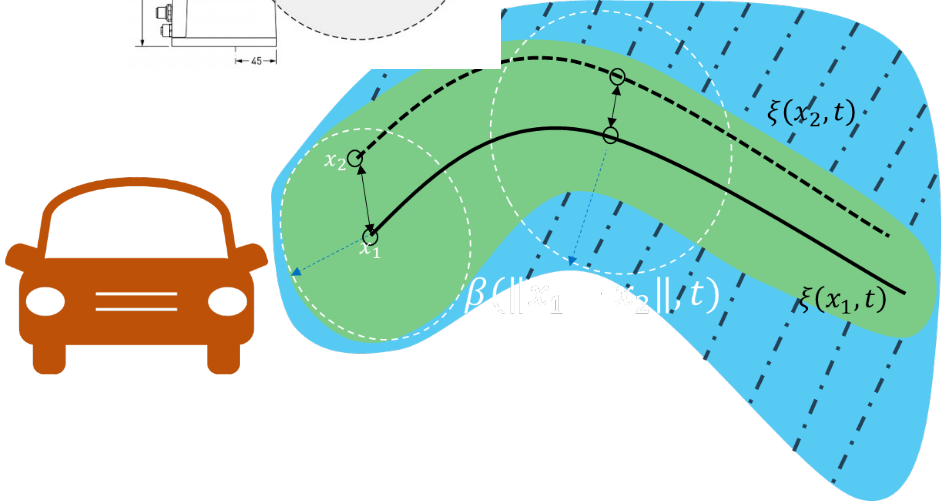
Reachability in a slide

Compute the ***forward reachable set,*** given system A with state space X, mode p ∈ P, set of initial states Θ, and look-ahead time T to find all states the system may enter within the time horizon

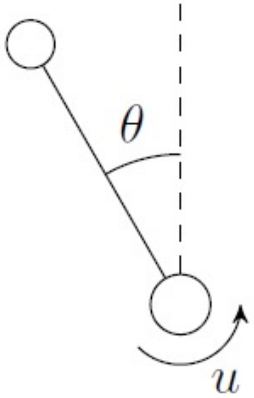
Compute the ***backward reachable set,*** given system A with state space X, mode p ∈ P, to find the set of initial states $\mathcal{X}_0$, from which the safe set can be reached or the unsafe set can be avoided

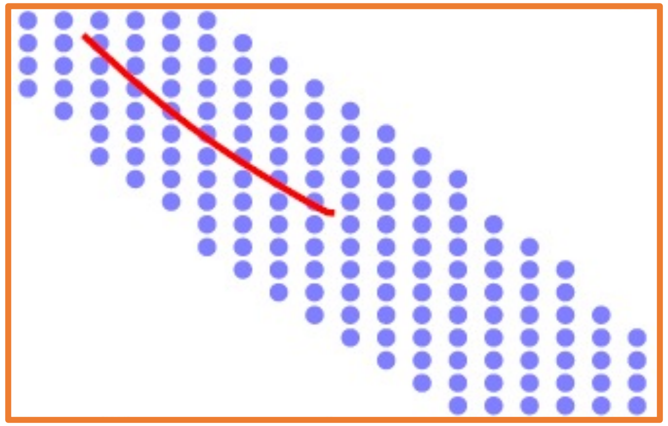


Forward Reachable Set

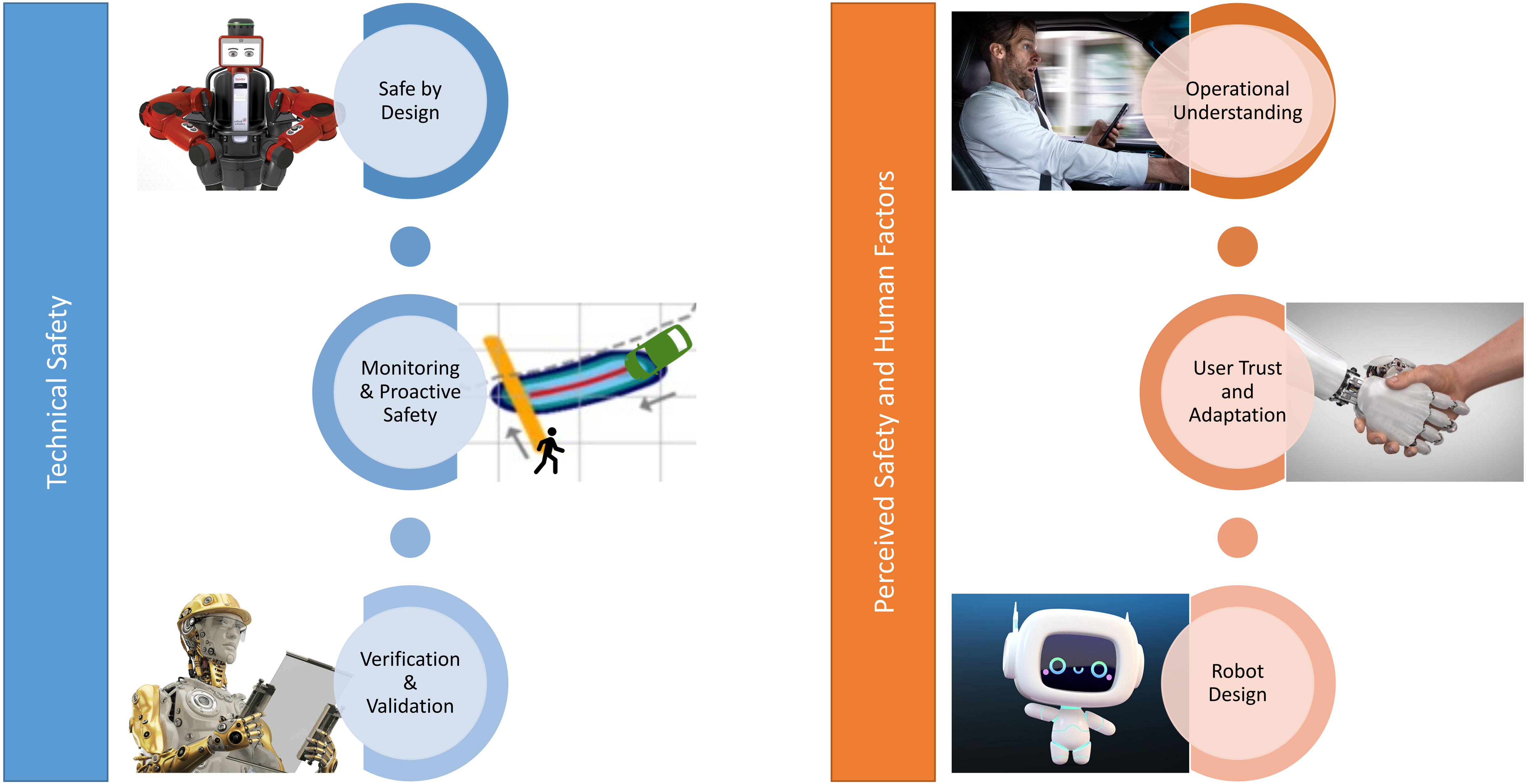


Backward Reachable Set

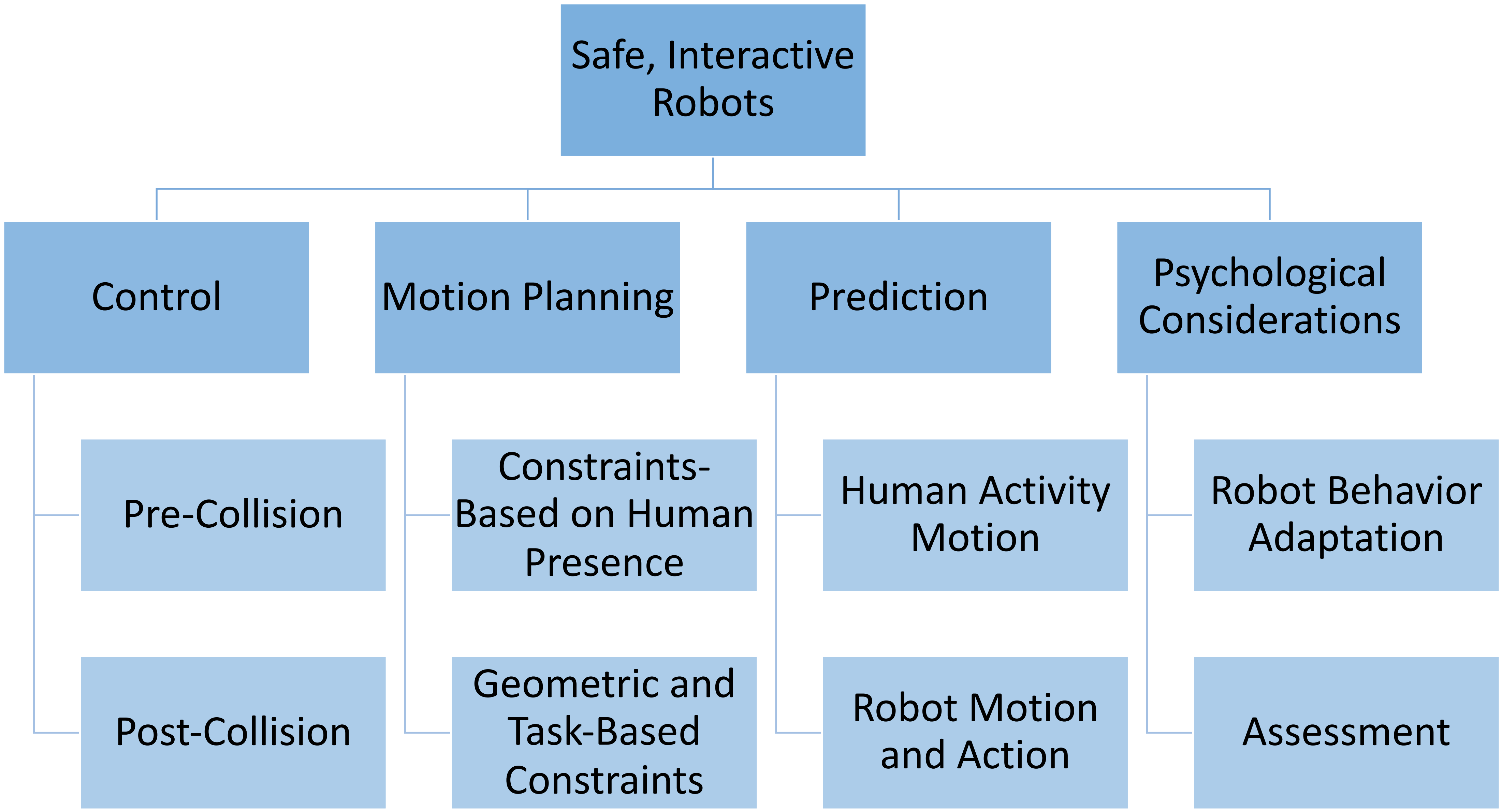




Robot Safety



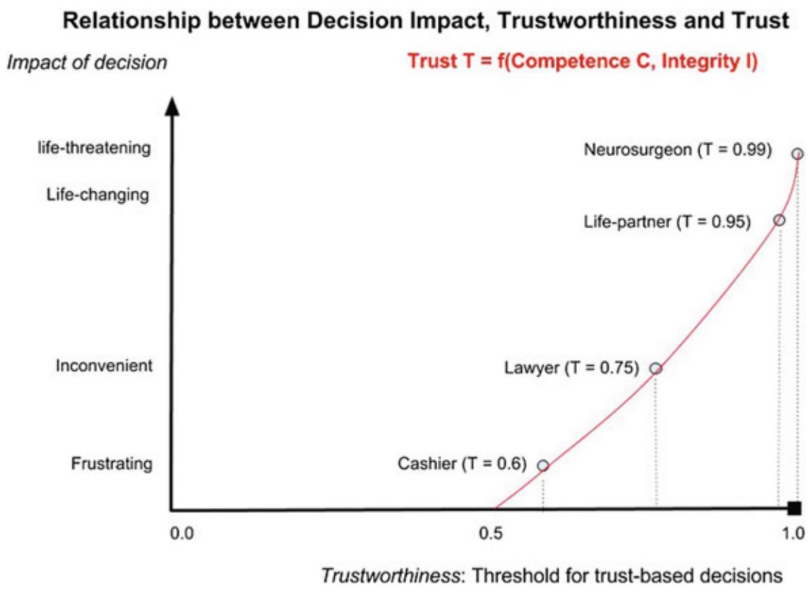
Extra Slides



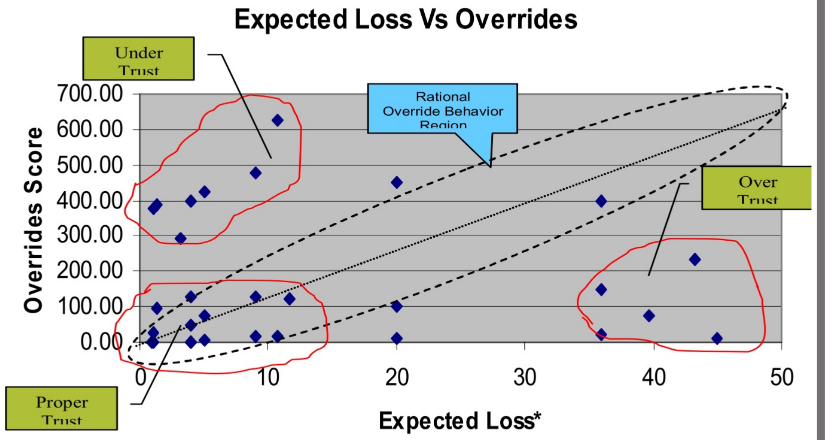
P. Lasota, T. Fong, and J. Shah. “A Survey of Methods for Safe Human-Robot Interaction.” Foundations and Trends in Robotics, 2014.

Many Facets of and Considerations for Trust

Context and Impact



Under- and Over- Trust



Expected Loss:

$$EL = \sum_{i=1}^{n} \frac{Expected\ Loss\ at\ trial}{Number\ of\ Overrides}$$

Physiological Response

H. A. Abbass, et al., "Foundations of trusted autonomy." Springer Nature, 2018.
A. Freedy, A., et al. "Measurement of trust in human-robot collaboration." IEEE International Symposium on Collaborative Technologies and Systems, 2007.
S. Sheng, et al. "A case study of trust on autonomous driving." ITSC, 2019.