Smart, Flexible, and Safe Industrial Mobile Robots: Performance Evaluation & Standardization Efforts

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Outline

- Introduction
- Developing Smart, Flexible, and Safe Next-Gen Mobile Robots
- Working with Industry, Developers, and End-users
- Performance Evaluation & Standardization Efforts
- Continuing Work & Concluding Thoughts

Industrial Mobile Robots (IMRs)

- IMRs (e.g. AGVs, Forklifts) are workhorses of the manufacturing, warehousing, distribution, and many other industries
- Widely used on factory floors for intra-factory transport of goods between conveyors/assembly sections, parts/frame movements, and truck-trailer loading/unloading
- *State-of-the-art*: Heavy dependency on infrastructure
  - Laser (reflectors), Inertial/Grid (magnets), Buried wire guidance
- Critical Enablers for Next-Gen Robots:
  - Ability to cope with unstructured, dynamic environments (*smart*)
  - Adaptability to human-centered collaboration (*flexible*)
  - Keeping humans out of harm's way (*safe*)

Measuring Performance of Intelligent Systems

- Performance Evaluation, Benchmarking, and Standardization are critical enablers for wider acceptance and proliferation of existing and emerging technologies
- Crucial for fostering technology transfer and driving industry innovation
- Currently, no consensus nor standards exist on
  - key metrics for determining the performance of a system
  - objective evaluation procedures to quantitatively deduce/measure the performance of robotic systems against user-defined requirements
- The lack of ways to quantify and characterize performance of technologies and systems has precluded researchers working towards a common goal from
  - exchanging and communicating results,
  - inter–comparing robot performance, and
  - leveraging previous work that could otherwise avoid duplication and expedite technology transfer.

Measuring Performance of Intelligent Systems

- The lack of ways to quantify and characterize technologies and systems also hinders adoption of new systems
  - Users don't trust claims by developers
  - There is lack of knowledge about how to match a solution with a problem

- Users may be reluctant to try a new technology for fear of expensive failure:
  - Think of the "graveyards" of unused equipment in some places

- …

ARRA-MSE Project Overview

- Commerce Department's American Recovery and Reinvestment Act (ARRA) Measurement Science and Engineering Research Grants
  - ***World Modeling for Autonomous Navigation In Unstructured and Dynamic Environments: Performance Evaluation and Benchmarking***
    - One of 27 projects funded (out of 1300 proposals) at higher-education, commercial, and nonprofit organizations in 18 states
    - Intended to "bolster U.S. scientific and technological infrastructure, increasing our nation's ability to innovate, compete, and solve scientific and technological problems"
    - Temple University and University of Maryland, College Park

Press Release

AGVs are an integral component of today's manufacturing processes; they are widely used on factory floors for intra-factory transport of goods. However, they require highly structured environments and reference markers installed throughout plants, which can carry prohibitively high maintenance and installation costs. AGVs could be much more widely used in manufacturing if they could cope with unstructured, dynamic environments and adapt to human-centered collaboration while still keeping humans out of harm's way. Having robots sense unstructured environments and automatically generate a sufficiently accurate world model is still an unsolved problem, and the solution requires a framework for generating accurate representations of the operational domain. This, in turn, requires scientifically sound and statistically significant metrics, measurement, and evaluation methodologies for quantifying intelligent systems' performance. To address these challenges, the researchers will create and experimentally validate a world modeling framework for unstructured manufacturing environments containing dynamic objects. The researchers also plan on creating reference data sets for end users, developers, and vendors, and to actively participate in standards efforts in this field.

Evaluation of Mapping and Navigation of IMRs

- Mapping is the process of creating a robot's internal representation of the physical world.
- **Goal:** To define of a framework to evaluate mapping algorithms with respect to their usability for navigation purposes in industrial environments.
- Towards this, we categorize the physical world into ***Environment & Obstacles***

Environment

- Denotes global changes of the physical world, which are perceived as long lasting, or more permanent
- Looking at the environment evaluates the ability of the map to support global navigation problems, e.g. path optimization
- Emphasis is on topological correctness over local geometric precision
- *Example: moving shelves, dynamic tire storage*

Obstacles

- Denotes local changes of the physical world, which are perceived as a temporal, non permanent
- Looking at obstacles evaluates the ability of the map to support local navigation problems, e.g. obstacle avoidance
- Emphasis is on local geometric correctness
- *Example: other vehicles, humans, accidental drops and spills*

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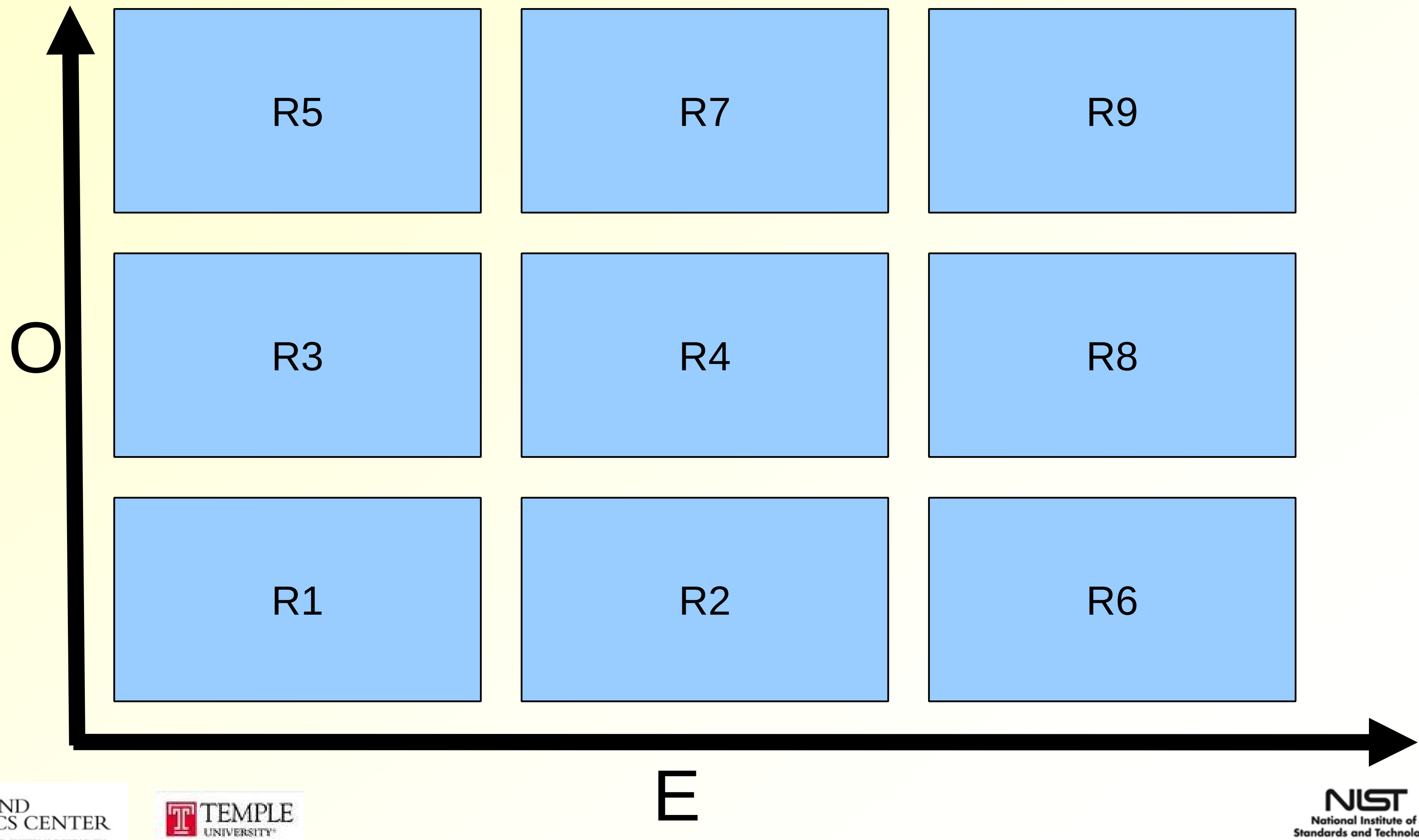
Evaluation of Mapping and Navigation of IMRs (2)

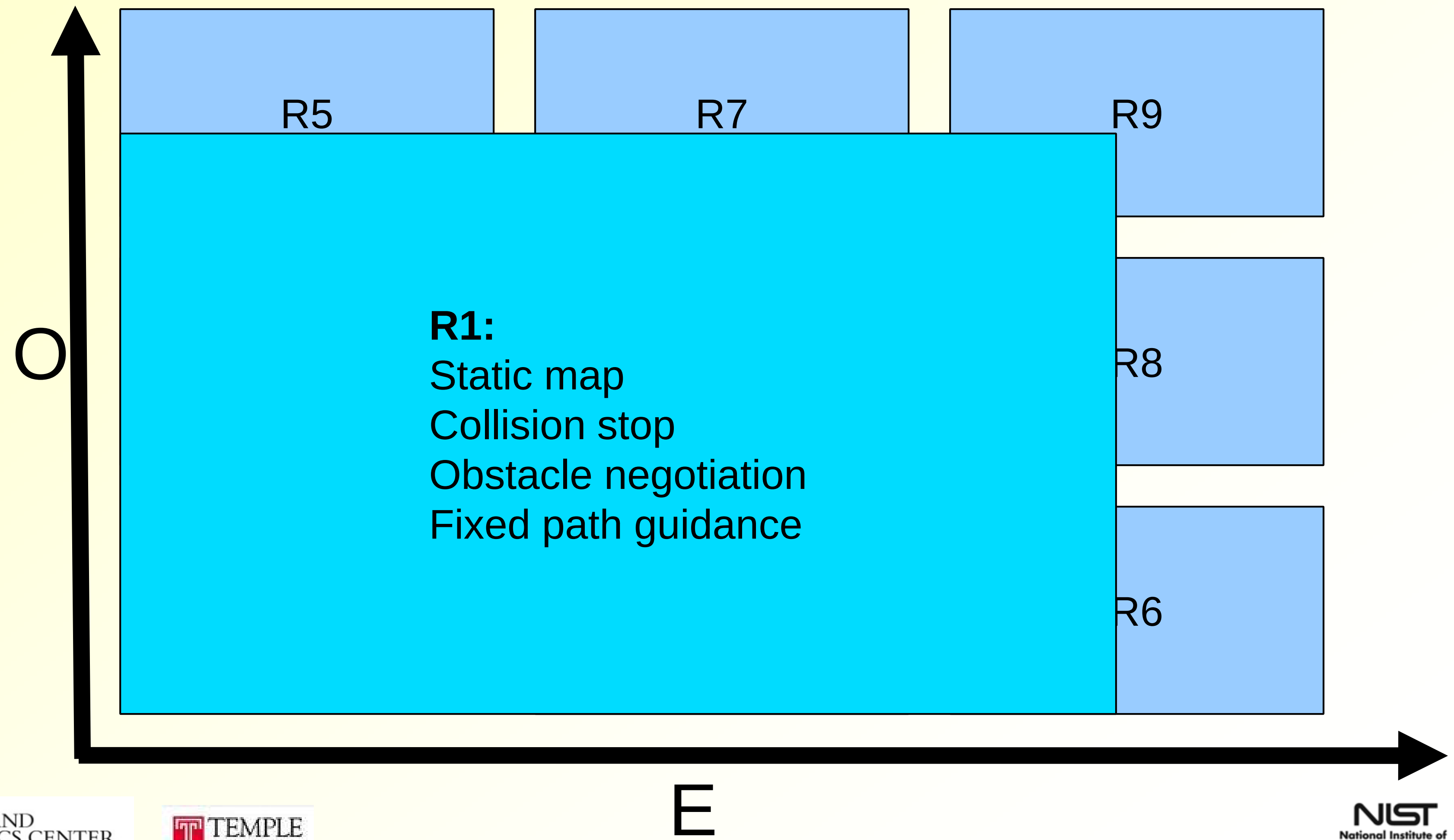
- **C**omplexity **L**evels of **E**nvironments and **O**bstacles (CLEO)
  - Environment and Obstacles axes are both split into three intervals, defining an increasing level of complexity:
    - Static
    - Predictably changing (Deliberately dynamic)
    - Unpredictably changing (Non deliberately dynamic)
  - CLEO provides a template for mapping/navigation characterization
  - CLEO defines a possible roadmap for developers and vendors

Evaluation of Mapping and Navigation of IMRs (3)

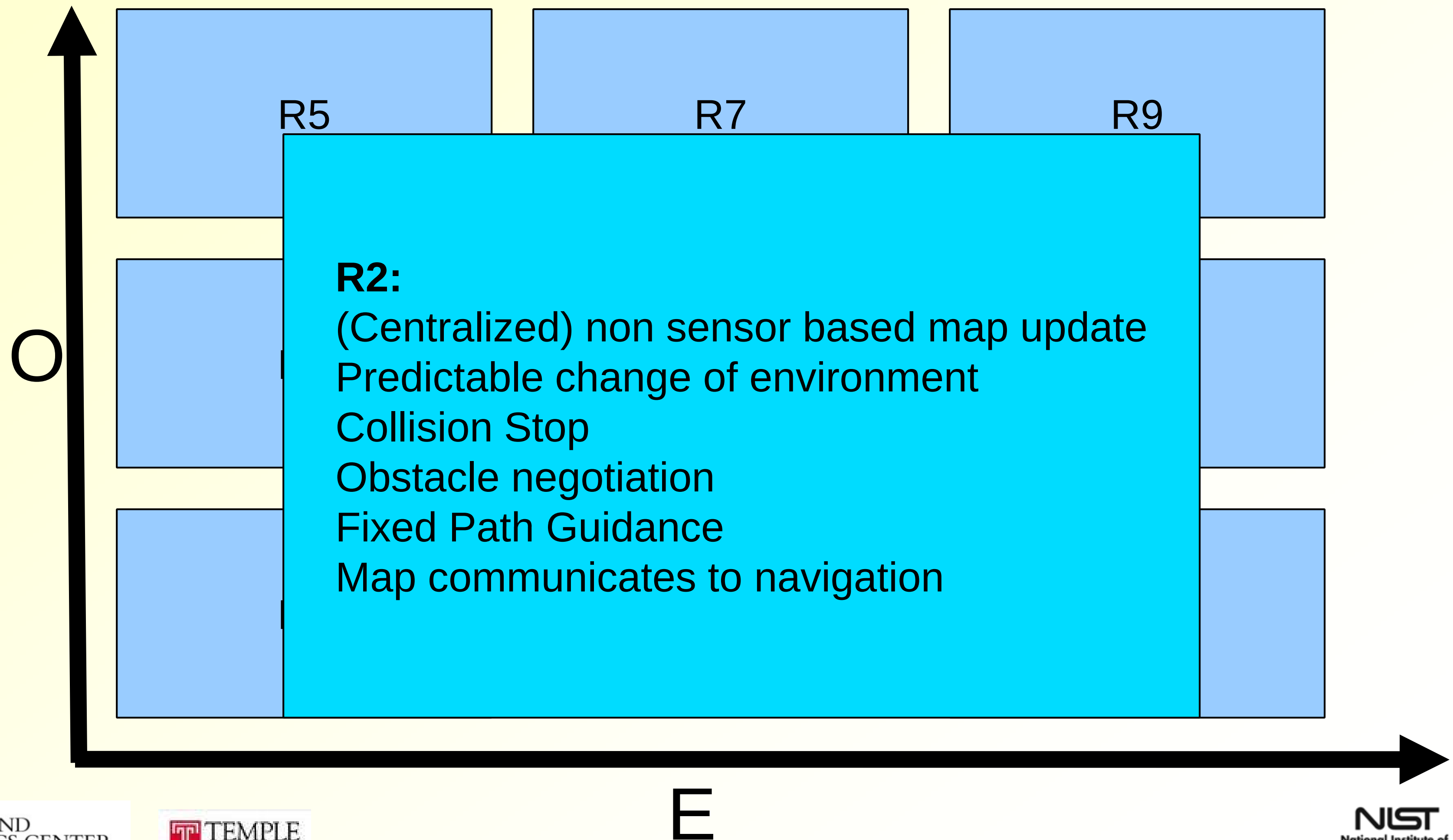
CLEO Categories of Environment and Obstacles define regions in the E-O Axes



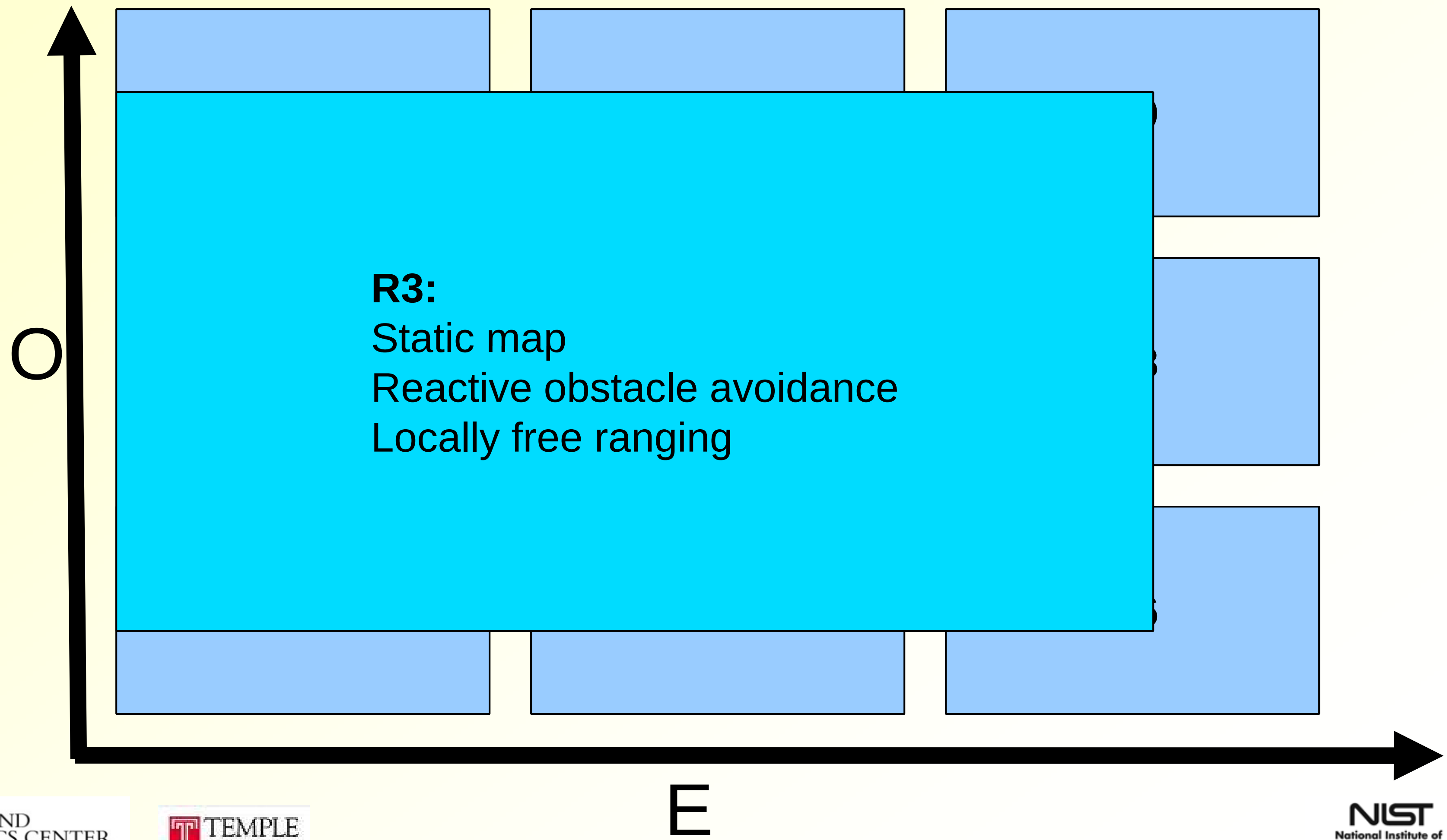
Evaluation of Mapping and Navigation of IMRs (4)



Evaluation of Mapping and Navigation of IMRs (5)



Evaluation of Mapping and Navigation of IMRs (6)



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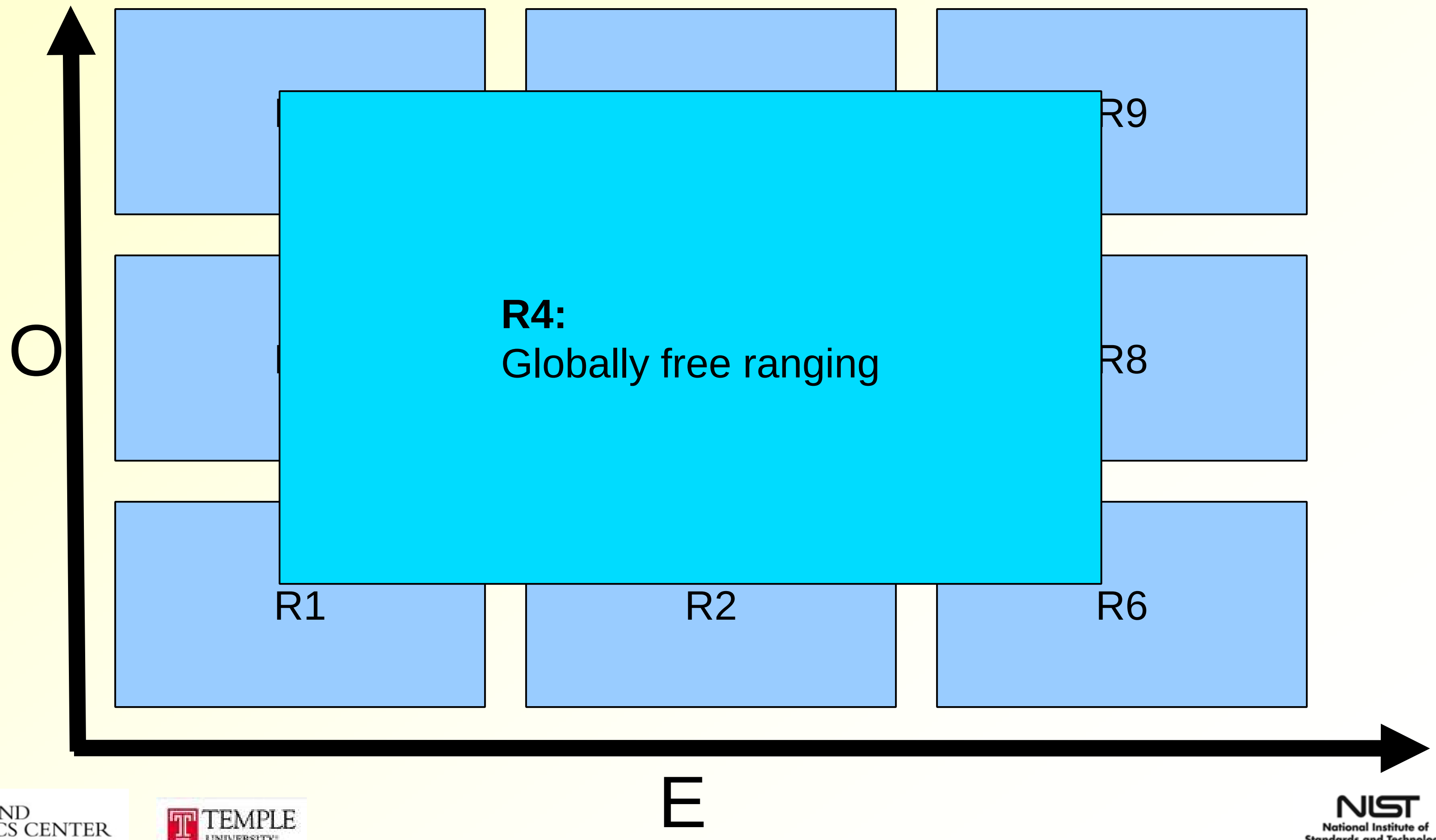
Evaluation of Mapping and Navigation of IMRs (7)



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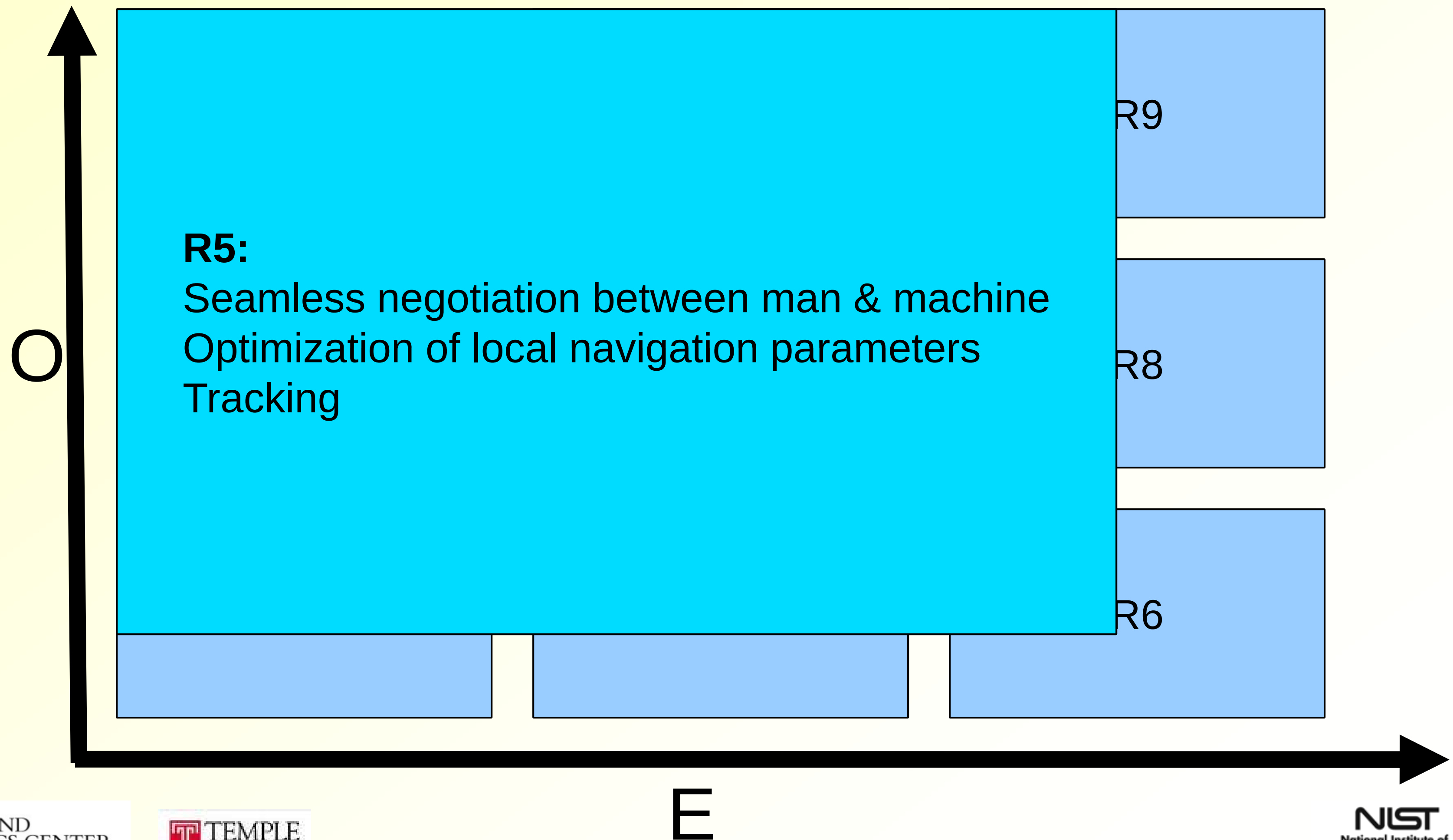
Evaluation of Mapping and Navigation of IMRs (8)



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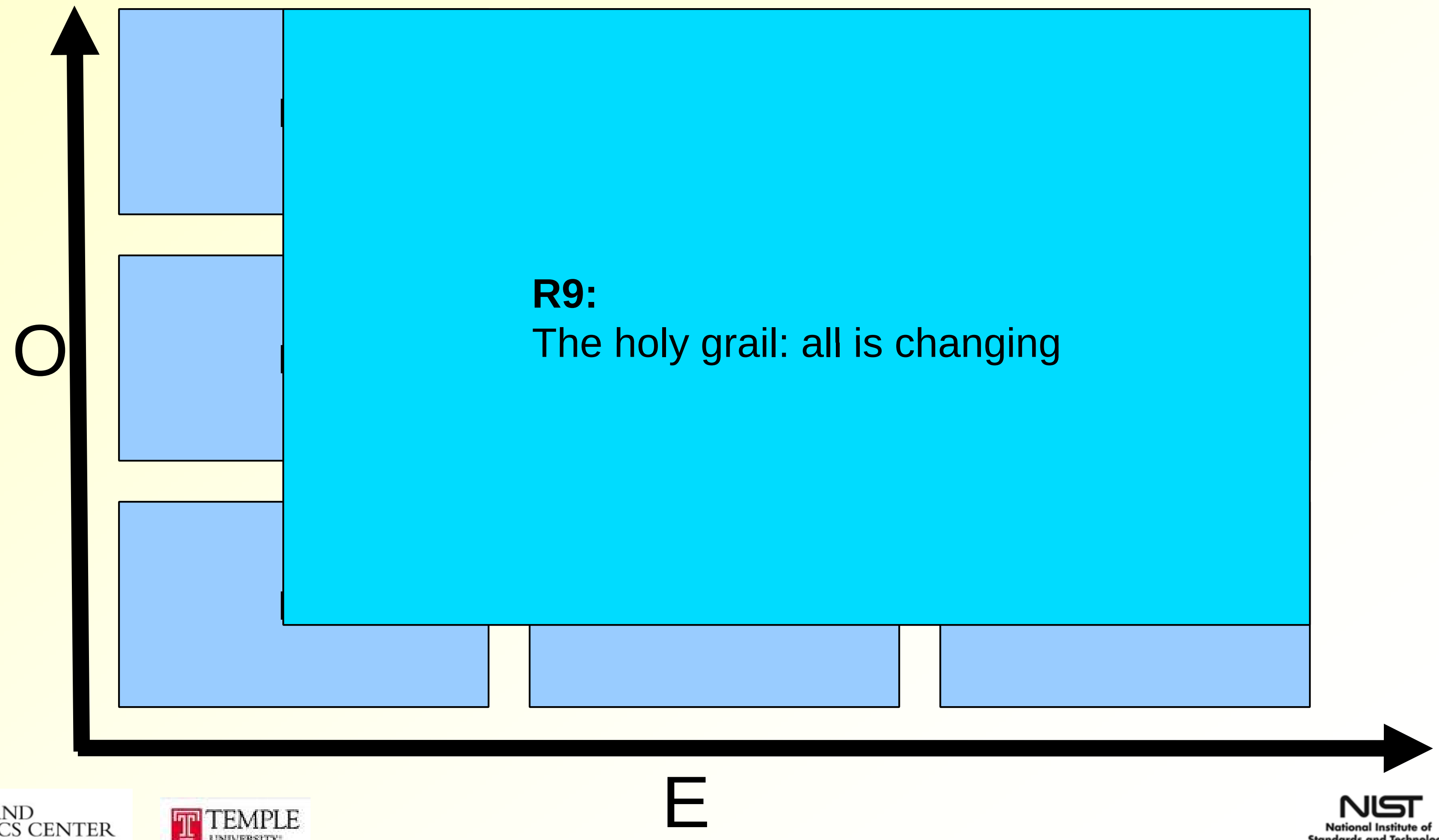
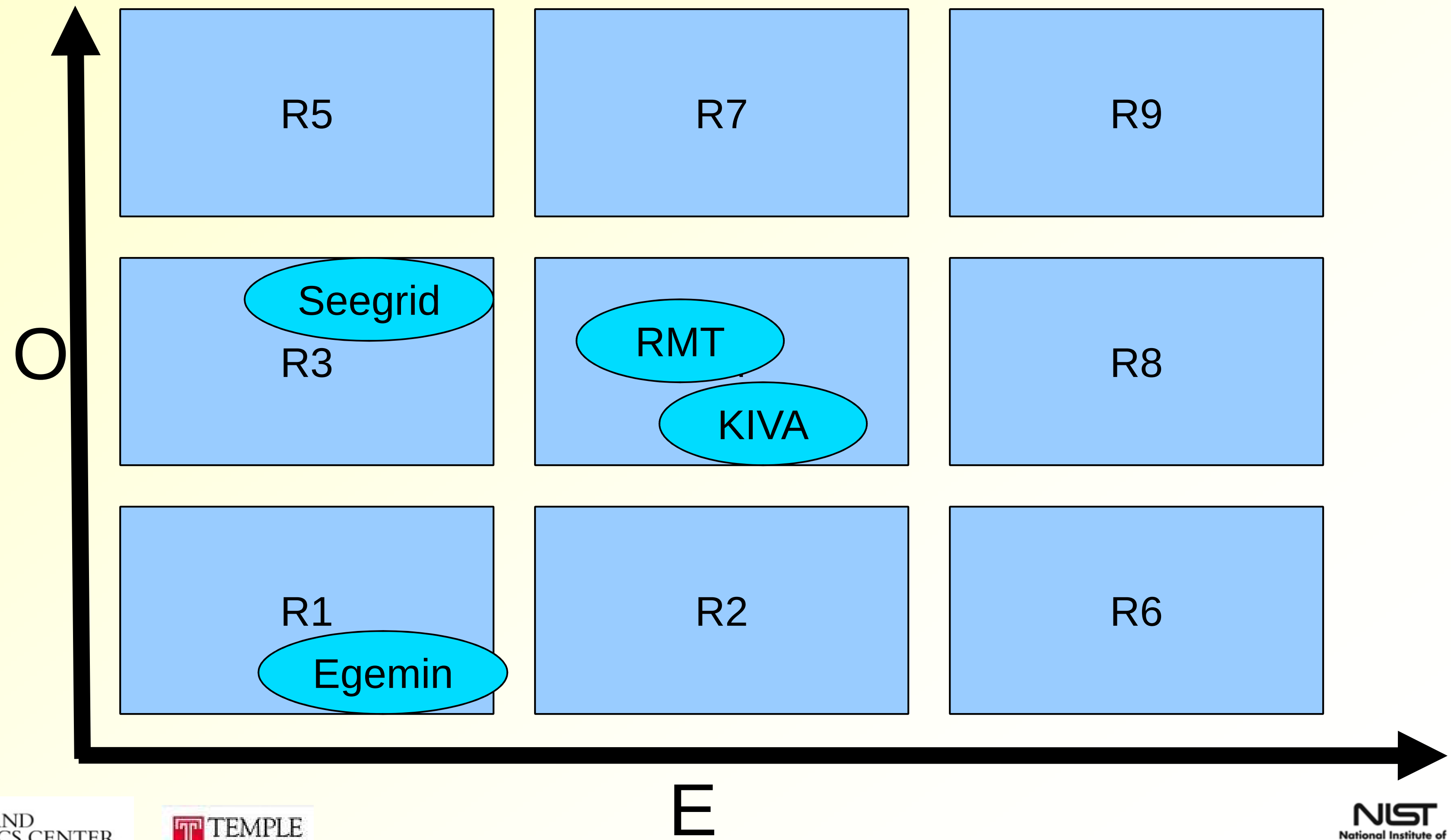


Evaluation of Mapping and Navigation of IMRs (10)



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Test Methods and Metrics

Static Map Metrics

- Completeness, consistency
- Geometric correctness/precision
- Topological correctness

Dynamic Map Metrics

- Training phase online? (can initial mapping algorithm deal with obstacles/clutter)
- Update automatic? Human in the loop?
- Update time for environment changes
- Correct distinction between environment changes and obstacles
- Obstacle tracking available?

- Dynamic Map Metrics naturally demand for real, physical world test environments
- Obstacles simulated using IMRs and mannequins

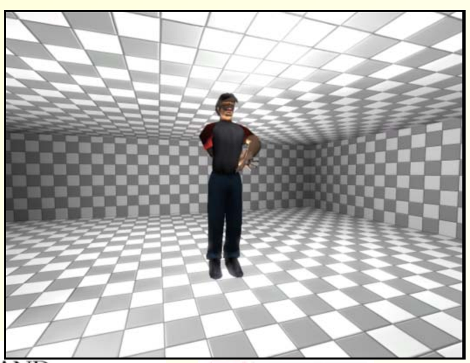
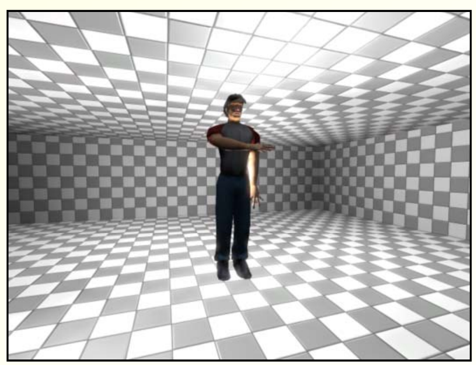
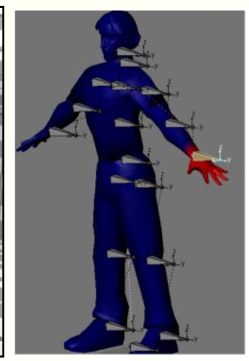
PRIDE Framework

- PRIDE (**PR**ediction **I**n **D**ynamic **E**nvironments) Framework
- Allows for the prediction of the future location of moving objects for the purpose of path planning for autonomous ground vehicles
  - Predictions can be fed to a vehicle's planning systems
  - Predictions can control vehicles to simulate realistic behaviors in dynamic environments
- To date, two prediction approaches have been applied to this framework
  - Short-term estimation-theoretic prediction (Kalman Filters)
  - Long-term approaches (Probabilistic, cost-based prediction & Fuzzy logic-based prediction)

Human-robot interaction with PRIDE

Goals

- Share a robot's workspace without any harm to humans or to the robot itself (*Flexibility and Safety*)
- Autonomous navigation of IMRs
  - Avoid collision with avatars and other IMRs
- Autonomous navigations of avatars (graphical representations of human beings) in manufacturing environments
  - Interact with other avatars and IMRs

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Human-robot interaction with PRIDE

- Autonomous driving of IMRs in manufacturing environments
  - New environments built in USARSim
    - Presence of loading/unloading stations
    - Presence of fences to separate hazardous fields from safe areas
- IMRs Accomplish missions with collision-free optimal path
  - Reach targets
  - Transport of goods between conveyors/assembly sections
  - Truck-trailer loading/unloading

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Human-robot interaction with PRIDE

- Intelligent behaviors for avatars (In Progress)
  - Build a network database of path nodes

Intersections of path nodes

- Path to follow depends on:
  - Goal of the avatar (reach target, wander in the environment, …)
  - Level of aggressivity of the avatar (Shy/conservative avatar would run away whenever an IMR comes closer)
- Aggressive avatar when IMRs approach
  - Stay at the same location
  - Move towards the IMR
  - Cross the path of the IMR on purpose

Safety Standards

ANSI/ITSDF B56.5 Safety Standard

- Industrial Standards Development Foundation (ITSDF)
- NIST has been working with ITSDF
- Work involves performance measurements of advanced non-contact sensors for AGVs

3D Sensor Experiments

- 2D line scanners work well with ground-based vertical obstacles
- Overhanging obstacles can be missed completely when directly in front of the sensor housing or if the obstacle is detected too late
- To ensure safety, ideally, the volume that completely surrounds the vehicle should be sensed
- 3D Flash LIDAR (7.5 m range; 176x144 pixels at 20 Hz) is being considered
- NIST has performed experiments that serves as background information to modify the ITSDF B56.5 Standard

Suggested B56.5 Text Changes

8.11.1.2 Noncontact Sensing Devices. If used as the primary emergency device, such **device shall be fail-safe** in its operation and mounting and shall stop the vehicle travel prior to contact between the vehicle structure and people or objects.

8.11.1.2.1 Test Pieces. The following test pieces shall be detected at 0%, 50% and 100% of vehicle speed in the main direction of travel and be positioned to be within the contour area of the vehicle (including onboard payload, equipment, towed trailer and/or trailer payload) as depicted in Figure 1:

(a) a test piece with a diameter of 200 mm and a length of 600 mm lying on and at 0º and 45º to the path of the vehicle and positioned at the left-most, right-most and center of the vehicle path,

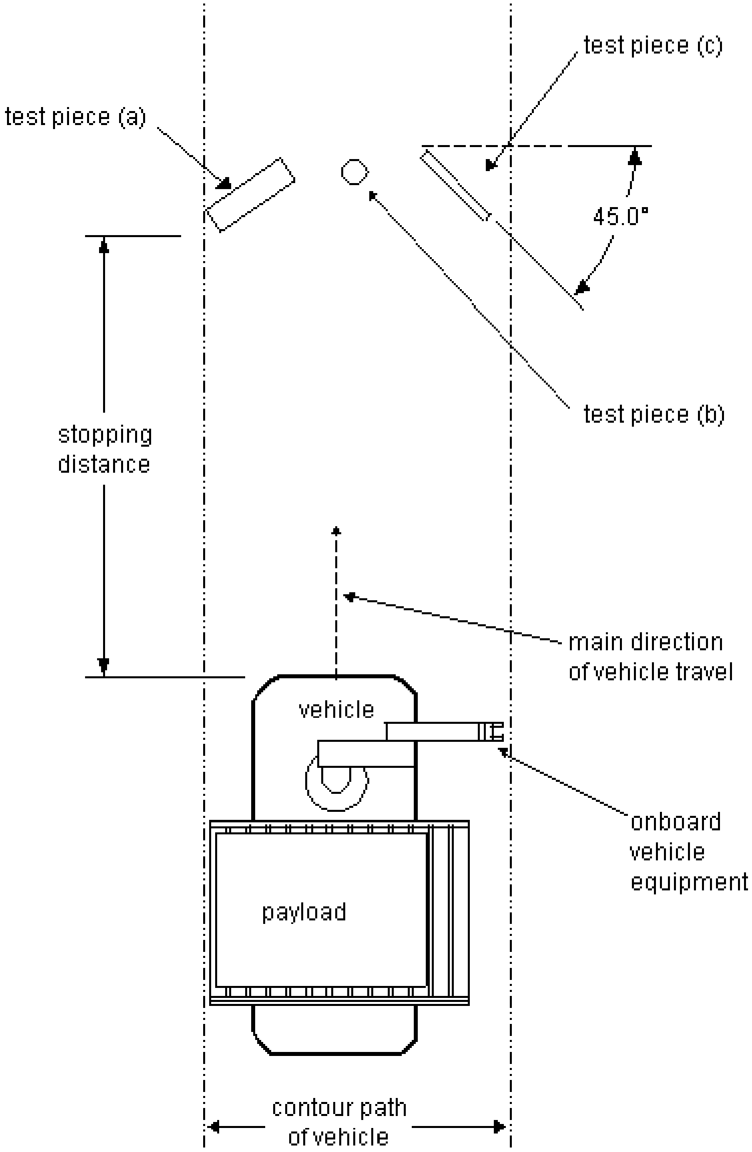
(b) a test piece with a diameter of 70 mm and a height of 400 mm set vertically and positioned at the left-most, right-most and center of the vehicle path,

(c) a test piece with a flat surface measuring 500 mm square set vertically and at test angles of 0º and 45º perpendicular to the path of the vehicle and positioned at the left-most, right-most and center of the vehicle path,

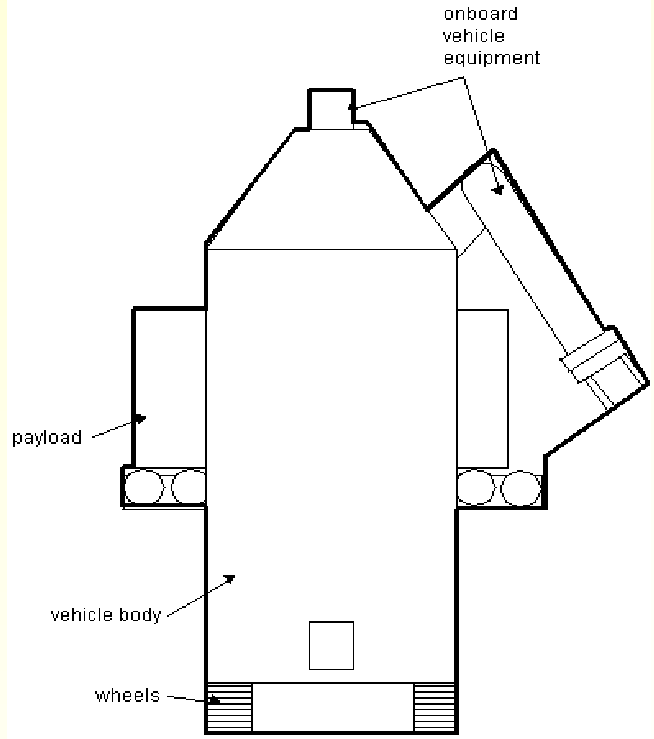
(d) note that (a), (b), and (c) test piece surfaces must be covered as follows:

- If optical sensors are used as object or person detection devices, the test pieces must have an external surface reflectance of 6% or less and optical density of 1.22 (e.g., black) or less as referenced in MIL-M-9868E.
- If ultrasonic (sonar) sensors are used as object or person detection devices, flat test pieces must have a highly reflective surface.

Suggested B56.5 Text Changes



Top view of vehicle path and test pieces



Front view of vehicle contour (bold outline) with overhanging payload, onboard equipment. Contour could also include a trailor and/or trailor payload (not shown).

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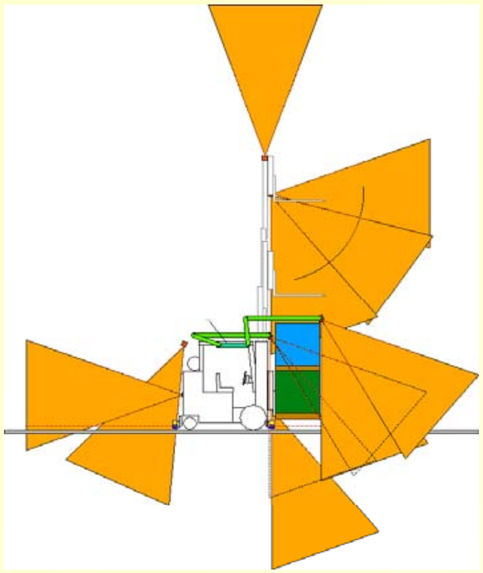
AGV Sensing Design using 3D imagers



(a)

(b)

- Tall loads where operator cannot see obstacles
- Overhead obstacles sensing
- Tilting sensor beneath and through fork tines

(a) Concept for ideal sensing for forklifts
(b) Forklift used in experiments showing sensor mount locations and sense directions (red arrows)

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Conclusions & Future Work

- Next-Gen mobile robots' requirements
  - Smart, Flexible, and Safe IMR Systems
- CLEO framework
  - characterizing mapping/navigation
  - roadmap for developers and vendors
- PRIDE framework for tracking humans
- ITSDF B56.5 Standards for AGVs

Thank you!

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