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DYNAMIC PERCEPTION WORKSHOP REPORT: Requirements and Standards for Advanced Manufacturing

Edited by:
Roger Eastman
Elena Messina
Tsai Hong
Hui-Min Huang
Mike Shneier
U.S DEPARTMENT OF COMMERCE
National Institute of Standards and Technology
Intelligent Systems Division
Gaithersburg, MD 20899-8230

and

Jane Shi
James Wells
GM Research and Development Center
Warren, MI 48090

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Patrick Gallagher, Director

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Requirements and Standards for Advanced Manufacturing

Roger Eastman, Elena Messina, Tsai Hong, Hui-Min Huang
and Mike Shneier
National Institute of Standards and Technology (NIST)

Jane Shi and James Wells
Manufacturing Systems Research Lab
GM Global Research & Development Center

Held in conjunction with
International Robots, Vision & Motion Control Show
Rosemont, Illinois

Tsai Hong (Chair) and Hui Huang (Coordinator)
National Institute of Standards and Technology (NIST)

Steering Committee (in alphabetical order)

Roger Eastman, Loyola
Jeff Fryman, RIA
Tsai Hong, NIST
Hui Huang, NIST
Frank Maslar, Ford
Elena Messina, NIST
Jane Shi, GM
Michael Shneier, NIST
Dana Whalls, AIA

June 11, 2009

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The opinions expressed in this Workshop Report are those of the workshop participants and are not the official opinions of NIST.

I. Introduction

The Dynamic Perception Workshop was held on the morning of June 11th, 2009, in conjunction with the International Robots & Vision Motion Control Show in Rosemont, Illinois. The stated objective of the workshop was:

To facilitate highly flexible automation in next generation manufacturing by:

- Developing standard metrics and test methods for the performance evaluation of advanced sensor and perception systems.
- Providing users, developers, integrators and researchers with quantitative measures of capabilities of perception systems. One example of a user-stated need is the following quote.

> "GM, as a sensor end user, will benefit from this standardized performance evaluation by being able to utilize sensors that have demonstrated their capabilities as defined by NIST standards first rather than going through an intensive trial-error learning process utilizing GM's resources"
>
> — Roland Menassa, General Motors, April 2008

The workshop was organized to solicit community input on how to define and develop the test methods and metrics for perception systems. Attendees came from the automotive industry, the sensor and metrology equipment industries, the robotics industry, the US Post Office, and academic institutions.

The workshop objectives grew out of community input gathered at the Smart Assembly Workshop and the Dynamic Measurement and Control for Autonomous Manufacturing Workshop. The Smart Assembly Workshop, held in Gaithersburg, Maryland in October 2006, was organized to identify key characteristics of smart manufacturing assembly, scientific and infrastructure challenges to deploying smart assembly, and opportunities to accelerate the development of smart assembly. A full report on the smart assembly workshop is available at http://smartassembly.wikispaces.com/. Among other findings, intelligent, flexible automation was identified as key to smart assembly.

An enabling technology for intelligent automation is dynamic perception, defined as the ability to sense the changing manufacturing environment for the intelligent control of automation equipment. To further refine the requirements of dynamic perception, the Dynamic Measurement and Control for Autonomous Manufacturing Workshop was held in Columbia, Maryland in October 2007. This workshop was organized to identify requirements for next generation robotics in dynamic environments, identify perception needs for visual servoing in autonomous assembly, and identify specific requirements for safe operation of robot arms and vehicles. The workshop report is available as a NIST internal report, NISTIR-7575[1].

Attendees at the 2007 Dynamic Measurement and Control for Autonomous Manufacturing Workshop concluded that, to advance beyond the current generation of machine vision systems on the manufacturing floor, the perception systems must:

- Be comprehensive, pervasive, and redundant.
- Be advanced by well-defined terminology, requirements, and scenarios.
- Be supported by reference standards for calibration and dynamic measurements.
- Be integrated into a community of successful commercial interests.
- Be validated for software and hardware safety and reliability by processes, test beds, and high fidelity simulations.

The present workshop, Dynamic Perception workshop, was organized to further refine these conclusions by looking more closely at terminology, requirements and scenarios.

II. Workshop Presentations

The workshop began with a set of presentations to explain its goals, scope, and approach, as described in the following sections. The workshop kicked off with welcoming remarks by Jeff Burnstein, President of the Robotic Industries Association (RIA). This was followed by presentations meant to set the stage for the active discussion.

II.1 An Example Process Model

The first presentation was entitled, "Standard Performance Test Method Development Process for Response Robots: Foundations for Progress in Manufacturing." This talk described a successful project in which NIST has coordinated the development of requirements, metrics, and test methods aimed at producing performance standards for robots applied to urban search and rescue (US&R)[2]. The process model used in this work was proposed as a straw man to be adapted for use in developing requirements and standards for dynamic perception.

The model is a user-driven process as depicted in Figure 1. For the emergency response robots case, the effort started by inviting end users, i.e., the Department of Homeland Security (DHS), Federal Emergency Management Agency (FEMA) and Urban Search and Rescue (US&R) Task Forces, to a series of requirement-generation workshops. The task force members described US&R operations and identified areas where they wanted the assistance of robots. Most responders were not at all familiar with robots and their

[1] Hong, Tsai H., Eastman, Roger, Bostelman, Roger V., Huang, Hui-Min, McMorris, B., "Proceedings of the Dynamic Measurement and Control for Autonomous Manufacturing Workshop," NISTIR 7575, May 2009.
[2] Messina, E., "Performance Standards for Urban Search & Rescue Robots: Enabling Deployment of New Tools for Responders," Defense Standardization Program Office Journal, July/December 2007, pp. 43-48.

present or potential capabilities. This posed the additional challenge of trying to envision what roles the robots could realistically be expected to take on during US&R missions.

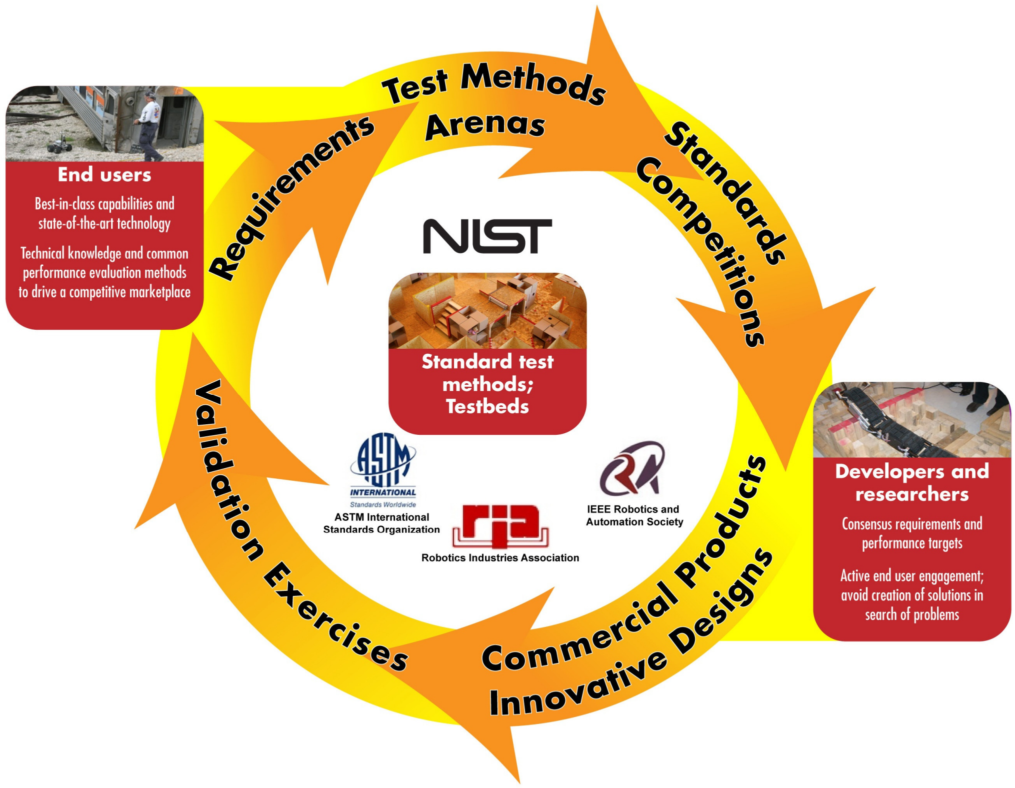


Figure 1: The Process Model for Standardizing Emergency Response Robots Performance Evaluation

The results of the workshops were sets of robotic performance requirements, expressed in operational terms. The following are the categories developed for US&R requirements:

- Terminology
- Human-Robot Interaction (HRI)
- Logistics
- Safety/Operating Environment
- Robotic Subsystems
  - Mobility/Maneuvering
  - Energy and Power
  - Sensing
  - Communications
  - Manipulation and Other Payloads
  - Chassis

Test methods are being developed to evaluate how well candidate robots meet the requirements. For example, the mobility test methods include how wide a gap a robot can cross, how steep staircases a robot can climb, and what types of terrain a robot can traverse, etc.

The essential elements of a test method are purpose, apparatus (physical test method setups), performance metrics, and evaluation procedure. For this particular project, the test methods become standards through a consensus balloting process within ASTM's E54.08 Homeland Security Applications, Operational Equipment Subcommittee.

The designed test methods must be thoroughly evaluated and validated. Periodically, NIST organizes large-scale response robot exercises, which bring together responders (users) with robot developers (manufacturers and researchers) at FEMA training facilities. All robots run through all relevant draft test methods, which enables the users and developers to provide feedback on the relevance and fairness of the tests. Training scenarios available at the FEMA facilities are used for exploring how robots can be utilized within search missions. This educates both responders and developers and allows for a common understanding of the goals of incorporating robots into US&R missions.

Competitions such as Robocup Rescue League[3] are also being utilized for "testing the tests." At these events, robots have to search arenas (also known as test courses) within a fixed amount of time, locate victims, and map the area. The arenas are comprised of test method elements, such as mobility, sensor, and manipulation tests. Research-grade robots that come to the competitions are often developed specifically to be able to complete the test courses. This stimulates innovative technology. Having a high volume of traffic and robot diversity running through the test courses helps shake out problems with the test methods. Verification and validation of the test methods are also done within test methods, located at NIST and elsewhere, where commercial robots are openly invited to participate. By repeatedly running the robots through the test courses, each of the essential elements of the designed test methods is being evolved to maturation.

The key concluding remarks of this presentation noted that it is important, for a new technology to become useful and usable, to:

- Measure performance in reproducible, repeatable ways that can correlate to use in the field.
- Develop concepts of operation and match the right characteristics to different deployment needs.
- Achieve buy-in from all the stakeholders, so that they perceive the benefits of this effort and support its advancement.

II.2 Background Presentation

The second presentation covered previous work done in the "Metrology and Standards for Advanced Perception Systems Project" by NIST and collaborators. The presentation covered previous workshops along with experiments conducted to develop metrology

[3] http://www.robocuprescue.org/

techniques to evaluate dynamic perception systems. The presentation material on previous workshops has been summarized in the introductory section and will not be repeated here.

The Metrology and Standards for Advanced Perception Systems Project develops quantitative, reproducible test methods to evaluate the robustness, accuracy and performance characteristics of advanced perception systems for general assembly and other macro scale manufacturing operations. For advanced use on the manufacturing shop floor, perception systems need to sense three-dimensional structure in a dynamic, uncontrolled environment. In particular, they must be able to accurately determine the six degree of freedom (6DOF) position and orientation of parts, people, robots and other objects in motion. This will enable new applications of automation, including continuous assembly where a robot interacts with a moving assembly line. A primary objective of the project is to develop dynamic 6DOF metrology that can provide calibration and ground truth measurements for perception systems.

The project encompasses a number of efforts, including providing dynamic metrology support for NIST work in AGV navigation evaluation and robotic arm calibration. This work is done as part of the NIST robot test bed, which includes a robot arm mounted on an overhead linear rail, AGVs, conveyer belts, sensors and a laser tracker for calibration and precise metrology.

The project has conducted collaborative experiments with the Robot Vision Laboratory of Purdue University in which the NIST laser tracker was used to provide ground truth for evaluation of the Purdue "Line Tracking for Assembly-on-the-fly" system. This system uses video cameras to track a part and direct a robot arm to insert a peg in a hole while the part is moving. The NIST work was able to produce measurements of the position and orientation of the part to 50 micro meters at 30 frames per second. The project is also working with the perception company BrainTech, Inc. to develop protocols for evaluating camera calibration and object pose algorithms.

II.3 Discussion Session Theme and Process

The workshop discussion was organized into two sessions, held sequentially. Each session was structured with an initial period for participants to generate ideas on note cards, a period to collect, post and sort the initial ideas, and a discussion period to refine, enhance and prioritize the initial ideas. The sessions were:

Session 1 - Manufacturing Perception Tasks and Scenarios
Facilitators: Elena Messina and Hui Huang
Objective: To develop a representative list of manufacturing scenarios

Issues:
Are there representative sets of manufacturing scenarios or tasks that can be identified as candidates for employing sensing to advance robotic capabilities?

Which of these manufacturing tasks may be the "low hanging fruit" in terms of perception system applications, i.e., where current or near-term perception technology, metrics, and standards can readily make an impact?

Concrete outcome: a list of near term scenarios where improved sensing would have an impact.

Session 2 - Dynamic 3D Sensor Requirements
Facilitators: Roger Eastman and Tsai Hong
Objective: To develop requirements for sensor performance

Issues:
What expanded capabilities, enhanced performance, and new information are needed from sensor and perception systems to advance manufacturing robotics?

What are the essential metrics for the sensory and perception systems (e.g., precision, response time, weights, working volumes, lighting requirements)?

Concrete outcome: a categorized set of requirements for advanced dynamic sensors.

III. Initial definition of scenarios

The workshop discussions started with each participant individually listing on note cards what they considered important requirements and scenarios for the future application of advanced perception systems on the manufacturing floor. The topics concentrated on discrete material transport, handling, and processing. They were organized, in a group effort, into two general categories:

• <u>Scenarios on the manipulation of materials and parts for logistics and processing</u>. These scenarios focused on how parts would be loaded onto and unloaded from pallets and bins and how the parts would be fed into and handled during assembly and processing steps. Particular examples were:

- i) Load a kit of parts through picking from small bins. (A kit is a technical term for a fixture that holds a number of parts needed for an assembly task. See Figure 2.)
- ii) Pick from a bin on a cart containing loose parts in a consistent orientation.
- iii) Unload and separate parts from a mixed-content pallet.
- iv) Pick a part from a kit and present it to an operator or load it into a machine.
- v) Build a logistics pallet with mixed stock items.
- vi) Mate rigid or flexible parts onto an assembly.
- vii) Process parts without using fixtures (machining, cutting, welding).

viii) Unload boxes as they arrive at a facility.
ix) Adapt quickly to production changeovers in low volume systems.

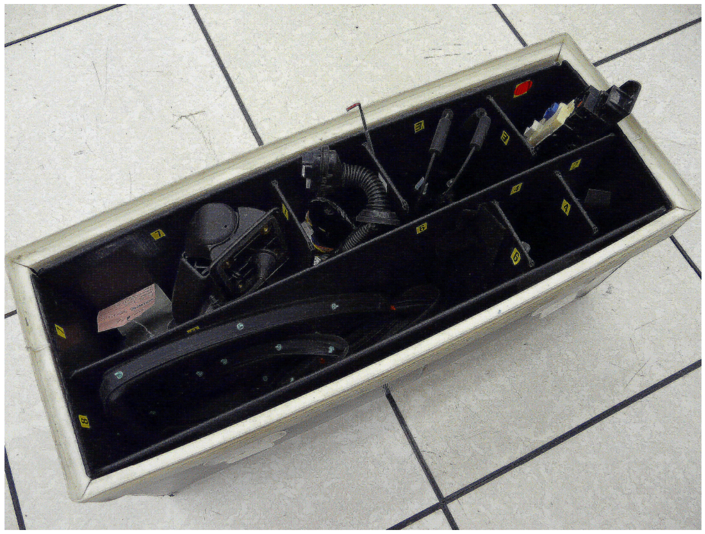


Figure 2. An example of filled kit with seven parts for a car door assembly task.

• Scenarios on the transport of parts through a facility. These scenarios focused on the use of automated guided vehicles (AGVs) and automated guided carts (AGCs) to move materials inside a facility. Particular examples were:

i) Locate an AGV on the factory floor.
ii) Navigate an AGV through human traffic.
iii) Respond to visual signals from a human operator.
iv) View a signpost and deal with blocked or obscured signposts.
v) Move heavy objects to designated areas without human interaction.

During discussions on these initial scenarios, the groups observed a few patterns and implications. First, most of the scenarios dealt with material handling: getting parts and material to the right place and in the right orientation. Only one of the initially-offered scenarios dealt with processing such as milling, finishing, cutting, and welding. The general observation was that, operating in an unstructured environment, the key new difficulty is getting a part from a kit, bin, or cart into position for a process. The flexible automation system must handle the job of fixturing a part for a processing operation, and then the processing operation will have its own automation procedure. The sense from the group was also that, for near term advances in flexible automation, material handling is key and success would lead to the next step of automating flexible processing.

Second, several of the part manipulation scenarios dealt with integrating robots into existing human-scale, manual processes. A kit is a bin designed to hold a set of parts for easy access as a person works on an assembly, and traditionally, filling and using a kit has been a manual process. The scenarios listed to build a kit and to pick from a kit are examples of human-robot collaboration where the robot assists by doing tasks it performs well. These are assumed to be simply handling objects, and then passing parts to a human operator so he or she can carry out joining tasks, which are assumed to be more challenging and best done by a person. Increased use of human-safe, flexible robotics would enable mixed use of humans and robots, and imply that the processes must generally be at a speed and scale appropriate for people.

Participants noted advantages in automating kit-oriented tasks that can be integrated with manual processes. Currently, robots are fenced off due to safety concerns and human operators can only enter a robot's work area by shutting down the work cell. This means that all steps in the work cell must be automated, since humans can't be in the loop, and that the automation must be highly reliable and rarely require human intervention since that is very costly in time lost. Integrating human-safe robots into manual processes would allow people back into the work cell, enable them to intervene or take over when a robot malfunctions, and help adapt the technology to low or medium volume processes so small manufacturers could afford automation. Integration of robots into manual processes contrasts with re-engineering and advancing processes for fully automated work cells performing tasks not previously automated.

• Issues for specialization and customization of scenarios.

Ideally, manufacturing scenarios used to develop testing protocols and standards would be as general as possible and have wide application to manufacturing industries. However, participants noted that current uses of perception on the manufacturing floor are highly specialized and require considerable customization to adapt to a specific plant or production line. Over time, as machine and computer vision applications on the plant floor develop, they should become more robust and general. However, the technology remains much less adaptable than human vision, so in the short run many solutions will remain constrained to specific applications and particular requirements. To drive technologies into useful solutions, general scenarios may need to be specialized for different application areas. The implications include:

1) Being clear if a scenario and standard is aimed at evaluating current vision systems for today's processes, or encouraging development of emerging sensors, techniques, and systems that enable new solutions for processes. The two types of scenarios, validating current technology or encouraging new approaches, may lead to different conversations between vendors and end-users. Those that encourage new technologies will have to be adaptable and frequently updated.

2) Developing metrics and evaluation procedures that as much as possible apply to both general scenarios and to specific applications. It would be useful for manufacturers to have metrics that apply to their specific needs, but are not so specialized that they do not apply to other applications.

3) Taking into account the ability of a vendor to optimize or customize their system to perform a standardized task. This could be part of a metric to evaluate a perception system. For current machine vision applications, the vendor often invests considerable time in customizing and optimizing their system for an end user task. For tests against a standardized scenario, the permitted efforts for customization should be made explicit (whether permitted or not, and how much effort is permitted.) If customization efforts are permitted, the effort involved should be tracked and logged so it

can be used in evaluation. A system that can perform adequately out of the box may be considered more valuable than one that works, but requires considerable effort to fine-tune.

4) Insuring that calibration issues are included in metrics. Calibration can be critical for success. A system that works well when calibrated, but does not maintain calibration well, is less valuable than one that maintains calibration well, or that performs self-calibration while in operation. Metrics for evaluation may need to consider whether a perception system is robust against poor calibration, whether it gives feedback on the quality of current calibration, whether it has diagnostics for calibration issues, whether it self-calibrates under operation, and whether the degree of difficulty of calibration and operator training needed for calibration.

IV. Refinement of material manipulation scenarios

Most of the workshop time was spent on refining the material manipulation scenarios, generally defined as pick and place operations. The basic task was defined as identifying, locating, gripping, and orienting an item for transfer from a container to a destination. This could be done for logistics, assembly, or processing. The group considered the characteristics of materials and parts, how parts are stored and transported, environmental conditions, and other aspects of the task. The general purpose of the discussion was to define the dimensions along which the basic pick and place task varied, so a hierarchy of challenging tasks could be defined. There was a working assumption that the materials or parts could be treated as discrete, solid units rather than continuous or fluid materials. The aspects of the problem considered were:

- Item count. The number of objects to be selected from – whether parts are presented one at a time or in larger numbers.

- Item geometry. The shape of the object, which determines the number of stable positions, the number and nature of gripping points, the symmetries, and the nature of visual features.

- Item reflectance/emissivity and texture. The visual/radiometric surface of the object.

- Item visual features. The number and nature of distinctive features that could be used by a vision system, which are a result of geometry and reflectance.

- Item consistency. Whether the parts are all one kind or mixed and the allowable normal variability in a single part type (which may be higher if man-made.)

- Item flexibility. Whether the part is rigid or flexible/compliant and whether it includes hanging subcomponents like a wiring harness or a bundle of hoses.

- Item grip points. Where and how the part can be gripped, including the choice of end effector needed and how small and/or forgiving the grip points are.

- Item size. Whether the part is very large and heavy, which introduces a number of constraints.

- Container type. The nature of the container from which parts are picked. For example, a bin could be a cardboard shipping container, a pallet, a rigid plastic bin, or a segmented kit.

- Container interference. If the container has a height or shape that occludes views of the parts and interferes with parts as they move out of the container.

- Container arrangement. How the parts are arranged for the robot to pick up. The parts could be individually presented, either flat on an assembly line or in some more general configuration such as in a fixed position kit, where each item has a nesting spot, in a bin or cart in a loose but consistent orientation, or in a bin in a random pile.

- Container motion and transport. How the container is presented – is it on a cart or other conveyor, is it stable, is it moving?

- Container internal stability. Whether the parts are stable within the container and whether they are likely to move or settle as they are being picked.

- Pick destination. Where the material or part is to be placed after the pick, whether in another bin, in a kit, in a chuck or fixture, or joined into an assembly.

- Pick destination rigidity. How stable and rigid the pick destination is, which influences whether perception is needed to check the pick destination before moving a part to it.

- Pick gripper stability/perception. If the part maintains its pose in the gripper, and if the sensor system can sense the gripped part.

- Pick destination planning. Whether the placement of the part requires considerable path planning to carry out, such as stacking containers or inserting a part inside a varying assembly, and whether the required motions avoid collisions and singular configurations.

- Environmental conditions. Lighting, noise, vibration, background motion, EM interference, humidity, temperature, building/sensor mount point stability, and all other factors external to the task itself.

While the group did not consider at length domain-specific applications and scenarios, there were a few observations about common situations. First was the ubiquity of objects shrink-wrapped for transport, which presents particular issues in sensing the objects and in determining safe grip points. Second was the palletizing of large products or bulky items, where the stacking of multiple layers of parts means that layers can drift from rigid positions and require sensing to detect offsets.

Once the group had listed a number of dimensions for the problem, it identified a number of requirements for the general task.

- Correctness of part identification. Can the sensor correctly identify parts?
- Accuracy of part location. Can a sensor system accurately locate an object? What is the quality of the sensed pose?
- Correctness/accuracy of grip point identification. Are the grip points on the object properly and accuracy located? Does the object need to be re-gripped?
- Accuracy of part placement. Can the robot/sensor system accurately place the object?
- Calibration of robot/sensor system. Can the sensor be easily and quickly calibrated to the robot?
- Anomaly handling. Can the sensor detect defective parts or anomalies in the container position?
- Speed/frequency of sensing. How quickly does the sensor system operate?
- Number/reality of candidates. Given a scene with multiple possible objects, how many candidates does the sensor system perceive, and how many of those candidates are false positives. How many objects does it miss?

An additional sensor issue identified was the relative importance of contact and non-contact sensing – what is the importance of touch and force sensing, and compliant grippers, relative to vision sensors?

V. Refinement of Automated Guided Vehicle (AGV) scenarios

In refining the AGV scenarios, the basic task was defined as the use of an autonomous vehicle to move parts or materials from place to place inside a facility. The discussion focused on the basic tasks of navigation, responding to guiding signals in the facility, avoiding obstacles and pedestrians, and the ability of the vehicles to carry different types of loads. The AGV discussion focused more on the capabilities of AGVs rather than on categorizing the aspects of the task. The capabilities considered were:

- Localization. How to localize an AGV on the shop floor.
- Navigation. Planning and executing a path through the facility.

- Scene mapping. How to use 2D or 3D imaging to map a scene for navigation or localization.

- Reading signposts. Ability to locate and interpret signposts, and to handle them when the signs are blocked or obscured.

- Responding to visual signals. Ability to perceive and respond to signals from a human operator.

- Detection and avoidance of obstacles. Ability to perceive and avoid obstacles, moving or static, including pedestrians and other AGVs.

- Nature of AGV. The type of AGV –a forklift, an AGV, an AGC (autonomously guided cart), or some other form of transport.

- Nature of cargo. What the AGV can transport and in what volume or weight.

- Environmental conditions. Lighting, noise, vibration, background motion, electromagnetic interference, humidity, temperature, floor condition and all other factors external to the task itself.

The requirements discussed were:

- Safety. Can the AGV operate safety without damage to humans, self or other elements of plant?

- Speed. How fast can the AGV operate and safely manage point-to-point delivery?

- Gripping requirements: Levels of difficulty? Loading and unloading speed. How quickly can the AGV be loaded and unloaded?

VI. Requirements for scenarios and sensor components

At the end of the workshop, a discussion was started, but not completed, on how to properly organize a test for evaluating data from range sensors. The discussion started with requirements for possible artifacts or targets, issues of resolution and accuracy, and the nature of an object's visual characteristics such as reflectance, emissivity and self-occlusion. The latter was defined as the characteristic of an object to hinder types of sensors, such as triangulation sensors, that require simultaneous views from two directions. This discussion was short and few conclusions were reached during the workshop. A decision made to pursue the issue post-workshop in follow-up discussions.

VII. Summary

The Dynamic Perception workshop was intended to further the development of standardized, reproducible, and portable test methods that can advance the technology of sensors and perception systems for new, flexible robotic and automation applications in manufacturing. The purpose of the test methods is to provide demonstrations and metrics for sensor performance that manufacturing firms can use to evaluate sensor-based products for deployment on the factory floor.

A central issue is finding universal, abstract test methods that are representative of factory floor conditions in smaller, summary formats, so that success in the test method predicts success in the factory. Manufacturing is a vast and complex domain, difficult to capture in limited scope test methods, and to advance robot and sensor technology it would be useful to identify and prioritize scenarios in manufacturing that can be translated into effective test methods. To this end, the workshop addressed four questions about advancing the use of perception systems in manufacturing robotics and automation:

1) Are there sets of manufacturing scenarios or tasks that can be identified as candidates for employing sensing to advance robotic capabilities?
2) Which of these scenarios or tasks are the low hanging fruit that can have a near-term impact?
3) What expanded capabilities and performance are needed to advance perception systems in manufacturing robotics?
4) What are essential metrics for evaluating perception systems in these scenarios?

The workshop discussions carefully addressed questions 1, 2 and 4, with question 3 on expanded capabilities implicitly covered by requirements developed in answers to the other questions.

A) The participants endorsed using a framework along the lines of the methodology used in the US&R standards project. In that project, test methods and standards evolve thorough strong communication and feedback among NIST and industry personnel. Rather than a fixed set of artifacts and test procedures, the test methods are based on flexible, adaptable test arenas and techniques that can be modified as industry participants advance the technology, and can be used to model a wide range of domain scenarios. This comes from the expectation that the technology is in a period of rapid development and broadening applications, and fixed test methods will eventually become obsolete.

B) The participants generally identified material handling tasks as the best first priority for candidate scenarios. During the initial phase in which participants individually listed possible scenarios, only one participant mentioned part processing such as machining, welding, cutting and painting while one other mentioned part joining. Other participants listed variations on the perception of objects for a broad range of picking and placing operations, and the open discussion centered on defining and refining pick and place scenarios. We concluded from this that perception during transformative operations, like cutting, welding or milling, is a lower priority at this time, and that initial success at perceiving objects for grasping and placement would be a natural first step to loading and handling objects during processing.

C) The participants spent the greatest time on characterizing pick and place operations that require perception systems to find, identify, locate precisely and assist in grasping parts and objects under very general conditions. The workshop produced 18 characteristics, as documented in section IV, to refine the definition of a pick and place operation. In short, the characteristics covered the nature of the item to be picked, the container from which the part is picked, and the destination. For example, the standard bin-picking operation would be defined as picking from a bin with many parts and placing the part in a known orientation at the destination. In the most general case, perception is required to locate and grasp the part, find obstacles as the part is moved to a new position, ensure the part is properly grasped, and analyze where the part is to be placed.

D) The 18 characteristics defined for pick and place operations cover considerable variations and do not narrow the pick and place scenario to concrete cases. The question is how to develop a sequence of concrete scenarios that require an increasing complexity of sensor and perception performance, advancing the technology step by step. In discussions during and following the workshop, the following two scenarios gained some attention.

a) Managing part shipments as they arrive (or depart) a factory, requiring perception of boxed and shrink-wrapped objects.
b) Kit loading and unloading as defined in Section IV.

The first scenario, managing shipping packages, has the advantage of being a limited but complete domain. Packages are typically of rectangular shape and of fixed reflectance patterns (cardboard or plastic, with tape and labels), and they are present in fixed orientations. The scenario has room for evolution as the nature of the packages can become more complex over time, and the scenario can lead to opening packages to unload, or loading packages.

The second, kit loading and unloading, has the advantage of offering well-defined, transportable test artifacts. A manufacturing assembly challenge might consist of a suitcase-style case that folds open with hinges that allow the two sides to be disconnected. In one half would be a set of parts of specified sizes and shapes in holders designed for each. The other half would be a bin. There could also be a mat with outlined spots for each part.

The challenge kit would support a number of tasks. All the parts could be dumped in the bin side and then picked and placed onto the kit side in the designated locations. Alternatively, the kit side could be unloaded part by part into the bin. For evaluating robot precision in grasping, the kit side could be unloaded onto the mat to match the outlines (there are no supporting sides to guide a part.) The parts could be varied to provide both a recognition task and an orientation and gripping task, and the parts could vary in difficulty of recognition and gripping. For mobile manipulators, the bin and kit could be separated. The parts could be designed with different geometries, such as prismatic, cylindrical, or ovoid, so that some are easier for pose calculations and some are harder. For single-arm robot systems, the assembly should either have, or come with, a stable base to build on.

Beyond simple parts handling, the kit could be assembled with or without human help. The parts could be designed for various assembly operations, such as peg-in-hole with gravity to hold them in place, screw threads, etc., and with different levels of difficulty. Increased dimensional tolerance could intentionally be added to the base parts to make assembly easier, but also to prevent the robot using dead reckoning for assembly. Over time, the kits could be made more complex.

E) With less time dedicated to perception for AGV tasks, the participants came up with a shorter list of characteristics and requirements than for manipulation, and the list should be reviewed for expansion. The list emphasized AGV navigation, cargo capabilities, performance in differing environments, and response to visual signals from signs and humans. The participants did not develop concrete scenarios.

Acknowledgments

We wish to thank Jeff Burnstein for the wonderful introductory words and overall support for the workshop, and Jeff Fryman for the workshop arrangements including the conference room. We thank William Townsend from Barrett Technology Inc., Otto Geiseman from Automated Precision Inc., Mike Boudreau from Technology Brewing Corporation, Joyce Guthrie from United States Postal Service, Jane Shi and James Wells from GM, Gino Mastrippolito from US Army, German Holguin from Purdue University, and Brian McMorris from SICK all for their excellent ideas and fruitful discussions that contributed to this report.

Appendix

A. Call for Participation

Dynamic Perception Workshop
Requirements and Standards for Advanced Manufacturing

Users, developers, and integrators of advanced sensory and perception systems for manufacturing have the following common interests: Users need to have full confidence in the capabilities of the systems before investing in them. Developers need to understand the user requirements in order to develop saleable products. Integrators need a common framework to be able to select the best products for their application and know they will work well together. To meet these needs, standard metrics, evaluation processes, and calibration methods are vital. Existing robot standards cover topics including terminology, safety protocols, and performance evaluation for robot manipulators and vehicles, but there are no corresponding standards for sensing systems used in manufacturing. Integration of sensors into robotic systems will help manufacturers attain higher levels of adaptability and reliability in their operations. We thereby invite interested parties to participate in defining these standards.

The issues for workshop discussion include:

• Are there sets of manufacturing scenarios or tasks that can be identified as candidates for employing sensing to advance robotic capabilities?

• Which of these manufacturing tasks may be the "low hanging fruit" in terms of perception system applications, i.e., where current or near-term perception technology, metrics, and standards can readily make an impact?

• What expanded capabilities, enhanced performance, and new information are needed from sensor and perception systems to advance manufacturing robotics?

• What are the essential metrics for the sensory and perception systems (e.g., precision, response time, weights, working volumes, lighting requirements)?

B. Background Presentations
B.1 Measuring the Performance of Response Robots
Presentation on US&R program given by Elena Messina.

Standard Performance Test Method Development Process for Response Robots

Foundations for Progress in Manufacturing

Elena Messina
Intelligent Systems Division
National Institute of Standards and Technology
Gaithersburg, MD 20899

NIST's Mission

To promote U.S. innovation and industrial competitiveness by advancing

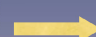
- measurement science,
- standards, and
- technology

in ways that enhance economic security and improve our quality of life

NIST's Role in Advancing Technology

- NIST works with end-users, vendors, and researchers to define performance *goals* for emerging technologies
- NIST develops tools and methods for measuring performance along a given "dimension."
- Vendors and researchers can measure their progress against target performance
- Users are equipped with data for making purchasing and investment decisions.
- "One size does not fit all" - we believe in measuring along a scale -- not in pass/fail!

Leveraging Success in Homeland Security Robotics Performance Measurement Methods



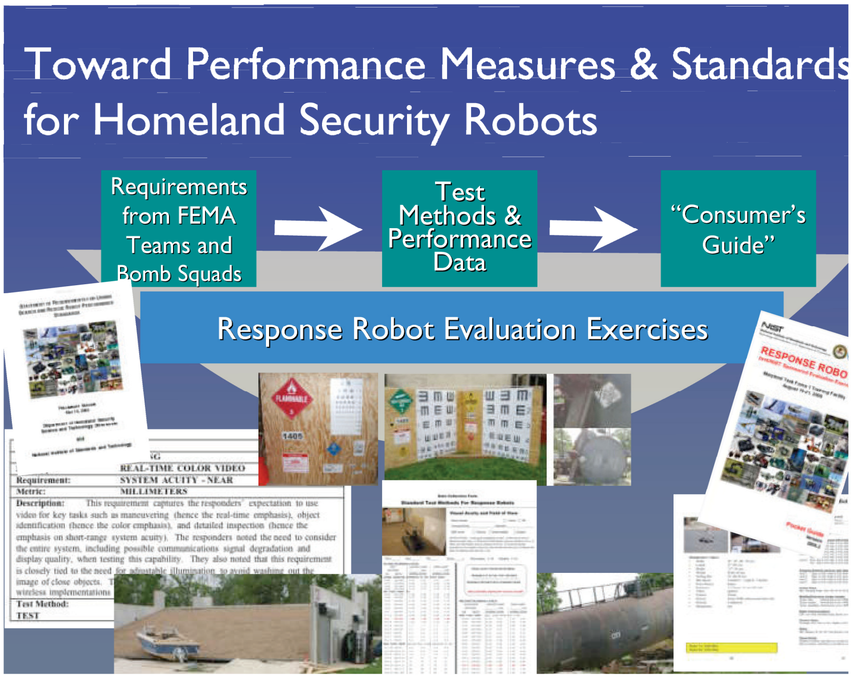
Program Goals

- Develop **standard test methods** for performance and use robots applied to response missions
  - Urban search and rescue (USAR) - sponsored by Department Homeland Security
  - Bomb-disposal - sponsored by National Institute of Justice
- Work within Consensus Standards Process:
  - ASTM E54.08 (USAR)
  - NIJ (Bomb-Disposal)
- Provide funding agencies at the federal, state, and local levels wit **quantitative measures** of capabilities of robots, along with usage guides to help them in their procurement and deployment decisions

What Must Response Robots Do?

(mobility, power, sensors, communications, operator interfaces)

What are the requirements?
How can we quantify robot performance in specific areas?
How can we abstract domain challenges?
How can we make them *reproducible, repeatable*?



End User (Responder) Requirements (US&R)

Requirements Category	Number of Individual Requirements	Category Definition
Human-System Interaction	23	Pertaining to the human interaction and operator(s) control of robot
Logistics	10	Related to the overall deployment procedures and constraints place for disaster response
Operating Environment	6	Surroundings and conditions in which the operator and robot have to operate
System		The main body of the robot, upon which additional components capabilities may be added. This is the minimum set of capabi (base platform)
Chassis	4	The main body of the robot, upon which additional components capabilities may be added.
Communications	5	Pertaining to the support for transmission of information to and the robot, including commands for motion or control of payloa sensors, or other components, as well as underlying support transmission of sensor and other data streams back to opera
Mobility	12	The ability of the robot to negotiate and move around the environment
Payload	7	Any additional hardware that the robot carries and may eithe deploy or utilize in the course of the mission
Power	5	Energy source(s) for the chassis and all other components o board the robot
Sensing	32	Hardware and supporting software which sense the environm
Safety	1	Pertaining to safety of humans and potentially property in th

Example Responder-Defined Requirements

Sensing	Real-time Video	Resolution of the image will be tested using visual acuity tests at given range. Image should be in color. Quality is evaluated through entire system (i. e., not standalone).
Logistics	Field Maintenance: Tools	Scale Defined: 1= Requires Special Tools; 3=Simple Tools (e.g., screw driver); 5=No Tools Required
Payload	Manipulation	Maximum Reach: measured in mm.

US&R Robot Deployment Categories

Ground: Peek Robots
Ground: Collapsed Structure--Stair/Floor climbing, map, spray, breach Robots
Ground: Non-collapsed Structure--Wide area Survey Robot
Ground: Wall Climbing Deliver Robots
Ground: Confined Space, Temporary Shore Robots
Ground: Confined Space Shape Shifters
Ground: Confined Space Retrieval Robots
Aerial: High Altitude Loiter Robots
Aerial: Rooftop Payload Drop Robots
Aerial: Ledge Access Robot
Aquatic: Variable Depth Sub Robot
Aquatic: Bottom Crawler Robot
Aquatic: Swift Water Surface Swimmer

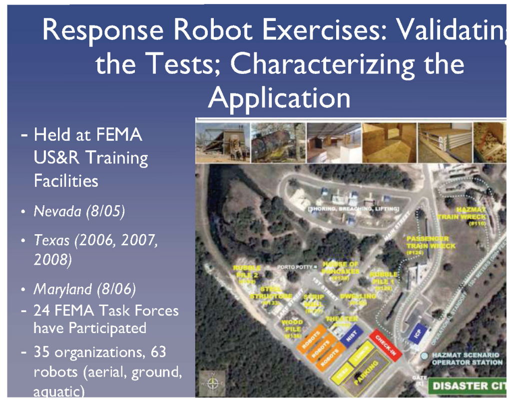
Example Deployment Categories for Robots

Robot Category	Ground: Peek Robots
Employment Roles(s)	Provide rapid audio visual situational awareness; provide rapid HAZMAT detection; data logging for subsequent team work
Deployment Method(s)	Tossed, chucked, thrown pneumatically, w/surgical tubing; marsupially deployed
Tradeoffs	Trade mobility, duration, sensing for increased expendability

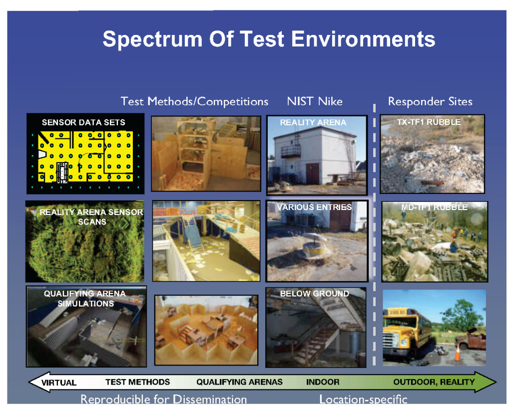
Example Deployment Categories for Robots

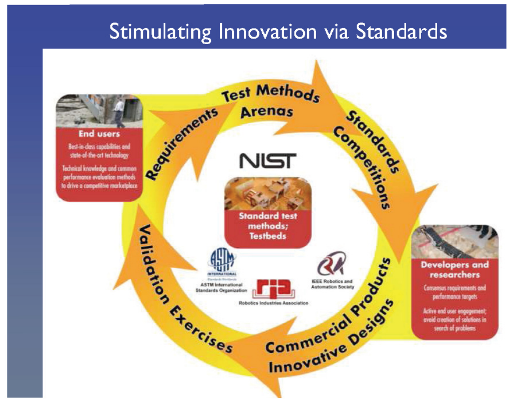
Robot Category	Ground: Non-Collapsed Structure –Wide Area Survey
Employment Roles(s)	Long range, human access stairway & upper floor situational awareness; contaminated area survey; site assessment; victim identification; mitigation activities; stay behind monitoring
Deployment Method(s)	Backpacked; self driven; marsupially deployed
Tradeoffs	Experience form factor for increased mobility, sensing, manipulation; mapping variant; spraying variant; breaching variant


Cache Packaging
Human Factors
Visual Acuity
Radio Comms
Manipulator Dexterity
INTERNATIONAL
Standards Worldwide
Example
Test Methods in
Standards Process
E54.08
Confined Space
Stairs
Mobility/Endurance
Situational Awaren
Directed Percept


Response Robot Exercises: Validatin
the Tests; Characterizing the
Application
- Held at FEMA US&R Training Facilities
• Nevada (8/05)
• Texas (2006, 2007, 2008)
• Maryland (8/06)
- 24 FEMA Task Forces have Participated
- 35 organizations, 63 robots (aerial, ground, aquatic)
DISASTER CIT


Response Robot Exercises: Understanding
Robots' Applicability to US&R


Spectrum Of Test Environments
Test Methods/Competitions
NIST Nike
Responder Sites
SENSOR DATA SETS
REALITY ARENA
TX-TF1 RUBBLE
REALITY ARENA SENSOR SCANS
VARIOUS ENTRIES
QUALIFYING ARENA SIMULATIONS
BELOW GROUND
VIRTUAL
TEST METHODS
QUALIFYING ARENAS
INDOOR
OUTDOOR, REALITY
Reproducible for Dissemination
Location-specific



NIST's Unique Role

- Independent, honest broker
- Convening disparate communities:
  - end users
  - robot manufacturers
  - researchers
- Access to application scenarios, international competitions
- Measurement infrastructure (e.g. UWB)
- Statistical significance
- Balancing generality, coverage, practicality of test methods

Summary

- Robotics and associated technologies provide a diverse and evolving set of capabilities for emergency response.
- To get these advanced tools into the hands of emergency responders, we are:
  - Measuring performance of robots in reproducible, repeatable ways that can correlate to use in the field
  - Developing concepts of operation and match the right characteristics to different deployment needs
  - Moving toward statistically significant repetitions to capture performance and reliability
  - Standardizing performance test methods through ASTM International and NIJ

B.2 Dynamic Perception Workshop

Introductory presentations on workshop purpose and background.

Dynamic Perception Workshop

Tsai Hong, Chair
June 11, 2009

Hui Huang
Coordinator

Workshop committee (in alphabetical order)

Roger Eastman, Loyola
Jeff Fryman, RIA
Tsai Hong, NIST
Hui Huang, NIST
Frank Maslar, Ford
Elena Messina, NIST
Jane Shi, GM
Michael Shneier, NIST
Dana Whalls, AIA

1

Workshop Purpose

- **To help industry achieve more flexible automation for next generation manufacturing by**
  - **Developing standard test methods for performance and use of advance sensor and perception systems**
  - **Providing users, developers, integrators and researchers with quantitative measures of capabilities of perception systems**

"GM, as a sensor end user, will benefit from this standardized performance evaluation by **being able to utilize sensors that have demonstrated their capabilities as defined by NIST standards first** rather than going through an intensive trial-error learning process and while utilizing GM's resources"

— Roland Menassa, General Motors, April 2008

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Agenda

8:00-8:05	Call to order	Tsai Hong
8:05-8:15	Welcome remarks	Jeff Burnstein
8:15-8:25	NIST experience with standards for first responder robots	Elena Messina
8:25-9:00	Background and instructions for breakout sessions	Tsai Hong, Hui Huang, Roger Eastman
9:00-10:50	Breakout sessions 1. Manufacturing scenarios 2. Requirements for perception	
10:50-11:00	Break	
11:10-11:50	Breakout reports and discussion	
11:50-12:00	Wrap up	Elena Messina/Tsai

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Jeff Burnstein
The President of Robotic Industries Association (RIA)

4

NIST experience with standards for first responder robots

(See RIA2009-Messina-output.ppt)

Elena Messina
Acting Chief of
the Intelligent Systems Division

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Background and instructions for breakout sessions

Tsai Hong, Hui Huang
and Roger Eastman
Researchers
Intelligent Systems Division

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What Must Next Generation Manufacturing Robots Do?

(mobility, power, ***sensors***, communications, operator interfaces)

What are the requirements?
How can we quantify perception performance?
How can we abstract domain challenges?
How can we make challenges *reproducible, repeatable*?

7

Operate in unstructured environments ...

(This one)

- AGVs in motion on shop floor
- Human-robot collaboration on assembly line
- Mobile manipulators
- On-the-fly assembly with dynamic visual servoing

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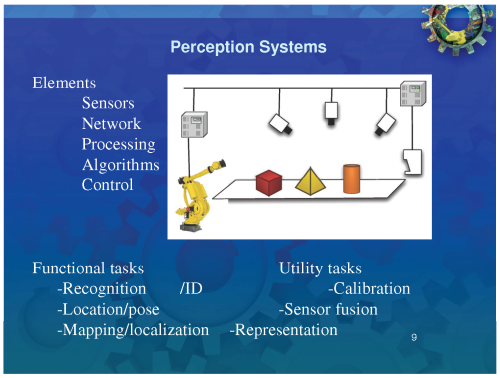
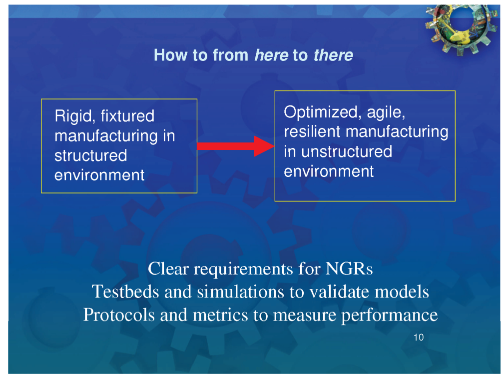
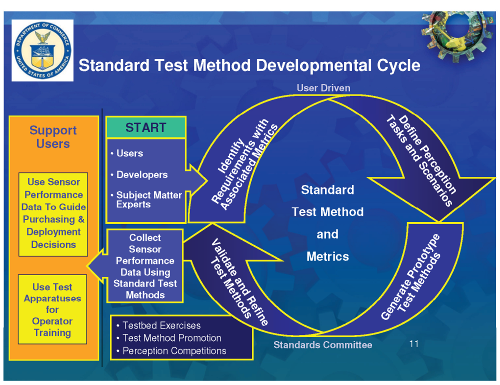
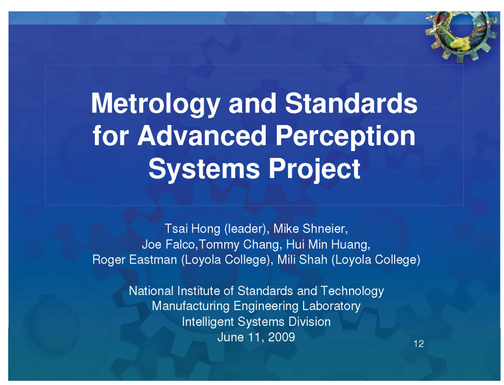

Perception Systems
Elements
Sensors
Network
Processing
Algorithms
Control
Functional tasks
-Recognition /ID
-Location/pose
-Mapping/localization
Utility tasks
-Calibration
-Sensor fusion
-Representation
9


How to from *here* to *there*
Rigid, fixtured manufacturing in structured environment
Optimized, agile, resilient manufacturing in unstructured environment
Clear requirements for NGRs
Testbeds and simulations to validate models
Protocols and metrics to measure performance
10


Standard Test Method Developmental Cycle
User Driven
Support Users
Use Sensor Performance Data To Guide Purchasing & Deployment Decisions
Use Test Apparatuses for Operator Training
START
• Users
• Developers
• Subject Matter Experts
Collect Sensor Performance Data Using Standard Test Methods
• Testbed Exercises
• Test Method Promotion
• Perception Competitions
Identify Requirements with Associated Metrics
Define Perception Tasks and Scenarios
Standard Test Method and Metrics
Generate Prototype Test Methods
Validate and Refine Test Methods
Standards Committee
11


Metrology and Standards for Advanced Perception Systems Project
Tsai Hong (leader), Mike Shneier,
Joe Falco,Tommy Chang, Hui Min Huang,
Roger Eastman (Loyola College), Mili Shah (Loyola College)
National Institute of Standards and Technology
Manufacturing Engineering Laboratory
Intelligent Systems Division
June 11, 2009
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Preceding NIST Workshops

- Smart Assembly
  - Gaithersburg, Maryland October 2006
  - Objectives:
    - Identify key characteristics of smart manufacturing assembly
    - Identify scientific and infrastructure challenges to deploying smart assembly
    - Identify opportunities to accelerate the development of smart assembly
  - Report available at http://smartassembly.wikispaces.com/
- Dynamic Measurement and Control for Autonomous Manufacturing
  - Columbia, Maryland October 2007
  - Objectives:
    - Identify requirements for next generation robotics in dynamic environments
    - Identify perception needs for visual servoing in autonomous assembly
    - Identify specific requirements for safe operation of robot arms and vehicles
  - Report available as NISTIR-7575, Booth #2148, CD

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Conclusions from Dynamic Perception Workshop

To go beyond the current generation of machine vision systems on the manufacturing floor, perception systems must:

- Be comprehensive, pervasive and redundant.
- **Be advanced by well-defined terminology, requirements and scenarios.**
- **Be supported by reference standards for calibration and dynamic measurements.**
- **Be integrated into a community of successful commercial interests.**
- **Be validated for software and hardware safety and reliability by processes, testbeds and high fidelity simulations.**

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Next Refinement

To go beyond the current generation of machine vision systems on the manufacturing floor, perception systems must:

- **Be comprehensive, pervasive and redundant.**
- **Be advanced by _well-defined terminology, requirements and scenarios_.**
- **Be supported by _reference standards for calibration and dynamic measurements_.**
- **Be integrated into a community of successful commercial interests.**
- **Be validated for software and hardware safety and reliability by processes, testbeds and high fidelity simulations.**

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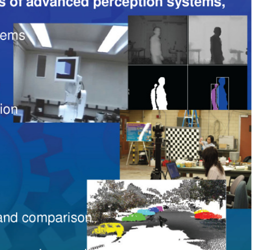
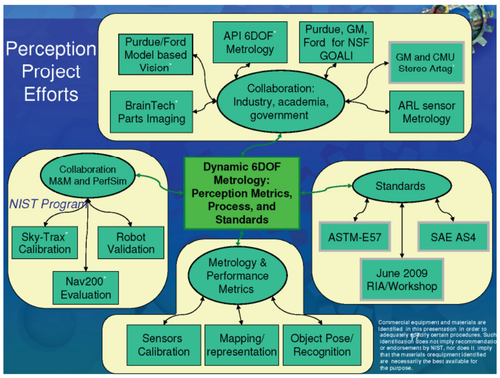
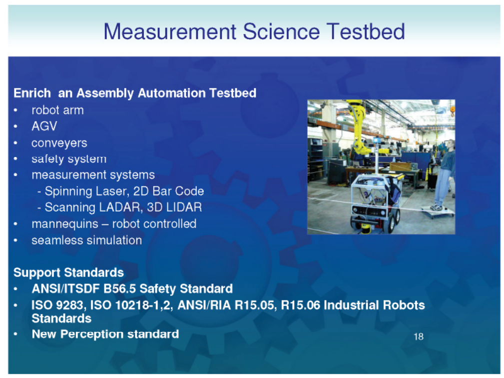
Metrology and Standards for Advanced Perception Systems

- **Develop metrology techniques and standards for performance measurements of advanced perception systems, including:**
  - Human tracking for safety systems
  - Vehicle navigation
    - Obstacle avoidance
    - Mapping and localization
  - Object recognition and inspection
  - Dynamic visual servoing
  - Sensor Calibration



- **Competencies for 3D perception**
  - **Calibration**
    For sensor evaluation, fusion and comparison
  - **Dynamic 6DOF**
    For evaluation of positional sensors that track people and objects


Perception Project Efforts
Purdue/Ford Model based Vision
API 6DOF Metrology
Purdue, GM, Ford for NSF GOALI
GM and CMU Stereo Artog
BrainTech Parts Imaging
Collaboration: Industry, academia, government
ARL sensor Metrology
Collaboration M&M and PerfSim
NIST Program
Dynamic 6DOF Metrology: Perception Metrics, Process, and Standards
Standards
Sky-Trax Calibration
Robot Validation
ASTM-E57
SAE AS4
Nav200 Evaluation
Metrology & Performance Metrics
June 2009 RIA/Workshop
Sensors Calibration
Mapping/ representation
Object Pose/ Recognition


Measurement Science Testbed
Enrich an Assembly Automation Testbed
• robot arm
• AGV
• conveyers
• safety system
• measurement systems
- Spinning Laser, 2D Bar Code
- Scanning LADAR, 3D LIDAR
• mannequins – robot controlled
• seamless simulation
Support Standards
• ANSI/ITSDF B56.5 Safety Standard
• ISO 9283, ISO 10218-1,2, ANSI/RIA R15.05, R15.06 Industrial Robots Standards
• New Perception standard
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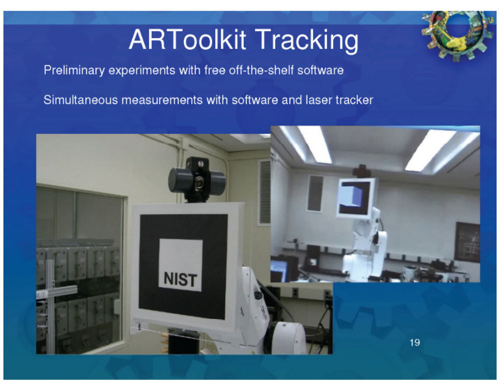
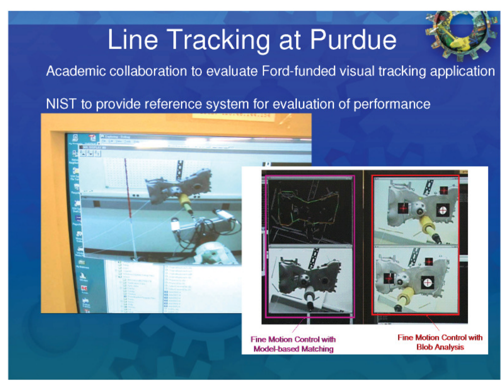
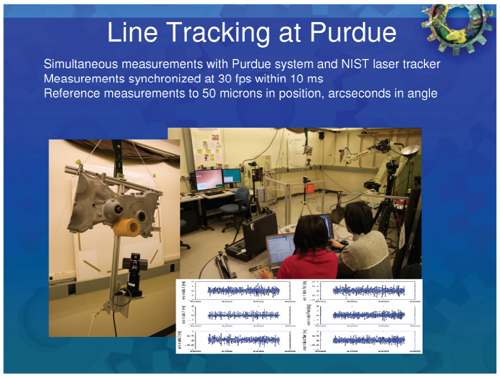
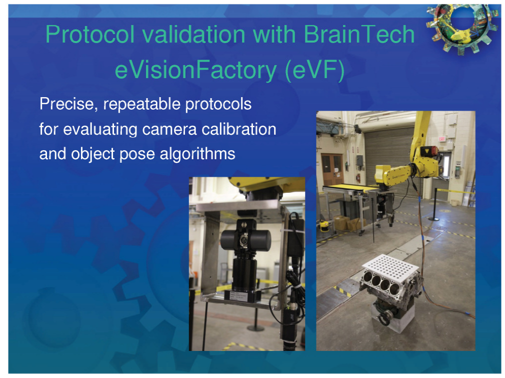
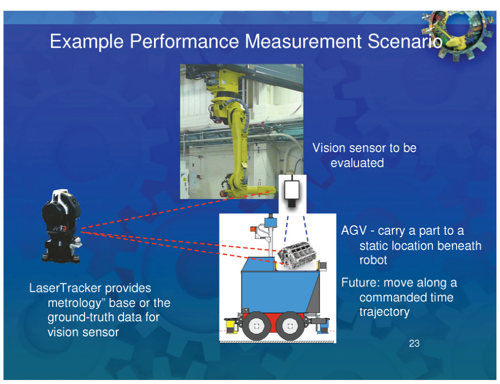

ARToolkit Tracking
Preliminary experiments with free off-the-shelf software
Simultaneous measurements with software and laser tracker
NIST
19


Line Tracking at Purdue
Academic collaboration to evaluate Ford-funded visual tracking application
NIST to provide reference system for evaluation of performance
Fine Motion Control with Model-based Matching
Fine Motion Control with Blob Analysis


Line Tracking at Purdue
Simultaneous measurements with Purdue system and NIST laser tracker
Measurements synchronized at 30 fps within 10 ms
Reference measurements to 50 microns in position, arcseconds in angle


Protocol validation with BrainTech eVisionFactory (eVF)
Precise, repeatable protocols for evaluating camera calibration and object pose algorithms


Example Performance Measurement Scenario
Vision sensor to be evaluated
AGV - carry a part to a static location beneath robot
Future: move along a commanded time trajectory
LaserTracker provides metrology" base or the ground-truth data for vision sensor
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Breakout Sessions
Session 1 - Manufacturing Perception Tasks and Scenarios
Facilitators: Elena Messina and Hui Huang
Objective: To develop a representative list of manufacturing scenarios
Session 2 - Dynamic 3D Sensor Requirements
Facilitators: Roger Eastman and Tsai Hong
Objective: To develop requirements for sensor performance
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Manufacturing Scenario Session Core Issues

Are there sets of manufacturing scenarios or tasks that can be identified as candidates for employing sensing to advance robotic capabilities?

Which of these manufacturing tasks may be the “low hanging fruit” in terms of perception system applications, i.e., where current or near-term perception technology, metrics, and standards can readily make an impact?

Concrete outcome: a representative list of near term scenarios where improved sensing would have an impact.

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Sensor Requirement Session Core Issues

What expanded capabilities, enhanced performance, and new information are needed from sensor and perception systems to advance manufacturing robotics?

What are the essential metrics for the sensory and perception systems (e.g., precision, response time, weights, working volumes, lighting requirements)?

Concrete outcome: a categorized set of requirements for advanced dynamic sensors.

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Dynamic Perception Workshop Breakout Session Schedule June 11, 2009

	Start time	Duration
Present approach and initial concepts; assign a scribe	9:00 AM	0:15
Each to generate ideas (note cards)	9:15 AM	0:10
Post ideas; organize, prioritize, and categories	9:25 AM	0:15
Discuss, analyze, and generate results	9:40 AM	0:45
Elect a presenter, generate/review slides	10:25 AM	0:25
Declare victory. Break	10:50 AM	0:10
Workshop plenary session resumes	11:00 AM	

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