Advancing Manufacturing Research Through Competitions

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ABSTRACT

Competitions provide a technique for building interest and collaboration in targeted research areas. This paper will present a new competition that aims to increase collaboration amongst universities, automation end-users, and automation manufacturers through a virtual competition. The virtual nature of the competition allows for reduced infrastructure requirements while maintaining realism in both the robotic equipment deployed and the scenarios. Details of the virtual environment as well as the competitions objectives, rules, and scoring metrics will be presented.

Keywords: manufacturing, autonomous vehicles, competitions, planning, traffic management, autonomous mobility.

1. INTRODUCTION

Automated Guided Vehicles (AGVs) represent an integral component of today's manufacturing processes. Major corporations use them on factory floors for jobs as diverse as intra-factory transport of goods between conveyors and assembly sections, parts and frame movements, and truck trailer loading/unloading. Automating these systems to operate in unstructured environments presents an exciting area of current research in robotics and automation. Unfortunately, the traditional entry barrier into this research area is quite high as researchers need an extensive physical environment, robotic hardware, and knowledge in research areas ranging from mobility and mapping to behavior generation.

Using a grant under the New Initiatives Competition program by the IEEE Robotics and Automation Society (RAS), the organizers, all employees of the Intelligent Systems Division within the Manufacturing Engineering Laboratory at the National Institute of Standards and Technology (NIST), proposed to address these barriers through the creation of a Virtual Manufacturing Automation Competition (VMAC). The competitive environment was designed to stimulate interest and participation among students while building a community that is competing to meet a common set of goals. The virtual nature of the competition was designed to reduce entry barriers by removing the need for an extensive physical environment and robot hardware, while a public domain code baseline and an open source requirement for code used in the competition reduced the breadth of knowledge that was required to participate, allowed participants to learn from their competitors, and self-sustain their research in their particular areas of expertise.

Competitions are an effective means of stimulating interest and participation among researchers by providing exciting technological problems to tackle. The progress and experiences from VMAC are expected to advance manufacturing automation research and development as the challenges within the competition are modeled after realistic problems faced by U.S. manufacturers. With the current global economic crisis, market competitiveness has probably never been more apparent. The United States is uniquely positioned to turn the current downturn into an advantage by wisely investing in research and development of robotic systems. In fact, the importance of such investments cannot be overstated if the US is to maintain a competitive edge in a global, volatile, and inter-dependent market.

We are leveraging open source simulation systems and the resulting algorithms from the collaborative efforts between participating researchers, students, NIST and IEEE-RAS are anticipated to advance the state-of-the-art. Open-source software and technologies enable quick implementations and testing of new algorithms with minimal effort. Our experience has shown us that it is an excellent means to maintain transparency and increase reliability. Perhaps more importantly, we envisage the competition to yield significant insights into what performance evaluation and benchmarking efforts are needed to design scientific experiments that will provide statistically significant results and breakthroughs. Benchmarking and standardization are critical for wide acceptance and proliferation of existing and emerging manufacturing automation systems. Leaving emerging robotic technologies to proliferate in an unguided direction comes with a high price: synergistic opportunities remain unrealized, and a lack of cohesion in the community hinders progress not only in manufacturing automation but in many domains such as service, search and rescue, and healthcare, to name a few.

The rest of the paper is organized as below: Sections 1.1 and 1.2 provide a brief overview of the origins and motivation behind VMAC and the simulation systems that serve as the basis for the competition, respectively. Sections 2 and 3 describe the competitions held so far and the associated results. Section 4 concludes the paper by discussing our thoughts on the future of VMAC.

1.1. VMAC's History

VMAC began in 2007 as a regional competition with a series of workshop/tutorials that included potential teams from the Greater Washington area (Maryland, Virginia, and the District of Columbia). The first workshop was a 2-day event that took place in October 2007 at NIST in Gaithersburg, MD. During this workshop, participants were acquainted with the provided software infrastructure and participated in the design of the competition's events. The software baseline included the USARSim (Unified System for Automation and Robot Simulation) system [1] and the MOAST (Mobility Open Architecture Simulation and Tools) robotic control framework [2]. A follow-up workshop was held at Hood College in Frederick, MD in February 2008 to track progress and provide hands-on assistance with any outstanding issues.

As discussed at the workshop/tutorials, the competition was to be based on real-world scenarios. The scenario chosen was a factory setting based off of existing small to medium factory layouts as shown in Figure 1. These factories have significant clutter, maze-like passageways of various widths, and dynamic obstacles. The objective was to have several Ackerman-steered AGVs pick-up packages at a central loading station, and deliver these packages to one of several unloading stations. The package destinations were encoded in an RFID tag on each package. This objective included the sub-problems of traffic management, route planning, path following, and docking. While the baseline code provided to the teams was capable of performing the objectives, it was far from optimal and not guaranteed to work in all circumstances. As time progressed, it became apparent that it was an overly ambitious set of tasks for the first year of the competition. A decision was made to break the competition into several discrete best-in-class tasks that would contribute to the scenario, and to leave the end-to-end objective for later. The tasks of accurate path following and docking were chosen as the VMAC tasks for the 2007-2008 competition year.

Figure 1: Typical small/medium manufacturing floor.

The first VMAC regional competition was held on April 18th 2008 at NIST and consisted of two tasks. For both tasks, the teams were required to accept a standard command message as input and were free to use as much of the provided infrastructure as they desired. For path following, the input consisted of a set of constant curvature arcs that were to be followed. These arcs were represented as a red centerline with a blue error radius as shown in Figure 2. As the path progressed, the arc complexity was increased and the error radius was reduced. Hood College produced the best-in-class algorithm for path following followed by George Mason University in a close second. The scoring criteria included the distance traveled before the first crossing over the error radius and the average path and speed deviation. The team's score was shown in real-time during the competition.

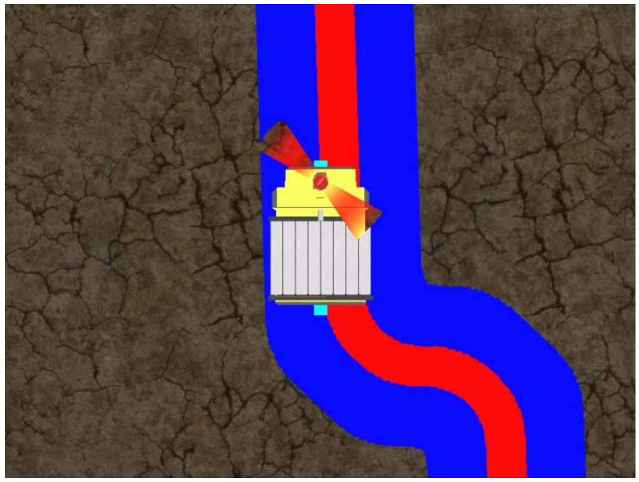

Figure 2: Simulated unit loader testing a path following algorithm. The center line of the path is the red line and the maximum error allowed for the center point of the vehicle is bounded by the blue region.

Docking ability was measured by placing the AGV in a room with a docking station. The AGV was required to successfully dock without a collision, where docking amounts to parallel parking a rear steered Ackerman vehicle. Upon successful docking, the AGV was placed in a smaller room and the procedure was repeated. Hood College was able to successfully dock in every room in which they were placed. With funding from the robot challenge held for the first time at the 2008 IEEE International Conference on Robotics and Automation (ICRA) in Pasadena, California, the winning team from Hood College was able to demonstrate their code for the first two days of the conference to all attendees. This conference demonstration launched the US National VMAC that was held at NIST in Gaithersburg MD on April 1-2, 2009, and the soon to be held International VMAC that will take place in conjunction with ICRA '09 in Kobe, Japan.

1.2. A Word on Infrastructure

The USARSim/MOAST framework provides a comprehensive set of open source tools for the development and evaluation of autonomous agent systems. These systems allow for initial development to occur in simulation with eventual transition to real hardware. From a theoretical perspective, one may easily argue that simulation accelerates the algorithm development cycle. However, in practice many in the robotics development community share the sentiment that "Simulation is doomed to succeed" [3] p. 209. This comes in large part from the fact that many simulation systems are brittle; they do a fair-to-good job of simulating the expected, and fail to simulate the unexpected. It is the authors' belief that a simulation system is only as good as its models, and that deficiencies in these models lead to the majority of these failures. It is for this reason that the USARSim system, which prides itself on model validation, has been chosen as a part of the infrastructure for the VMAC.

The first release of USARSim was produced in October 2005 by creating modifications to Epic Game's Unreal Engine 2 game engine[1] (see http://www.unrealtechnology.com/ for more information). USARSim provides realistic environments and embodiment for agents with the environments consisting of full 3 dimensional worlds that have photorealistic

[1]Certain commercial software and tools are identified in this paper in order to explain our research. Such identification does not imply recommendation or endorsement by the authors, nor does it imply that the software tools identified are necessarily the best available for the purpose.

textures and objects. Embodiment is aided by the Karma physics engine that allows for physics-based interactions with objects in the environment. Version 3.31, released in July 2008 offers 15 different sensors ranging from odometry to an omnidirectional camera, 23 different robotic platforms including wheeled robots, cars, tracked vehicles and flying robots, several robotic arms, and various robotic effectors such as factory conveyors, radio frequency identification (RFID) tag releasers, and grippers. Most importantly, several of the sensors and robots have undergone rigorous scientific validation in order to prove their similarities and difference from the real devices [4-6]. More information may be found at the USARSim website located at http://www.sourceforge.net/projects/usarsim.

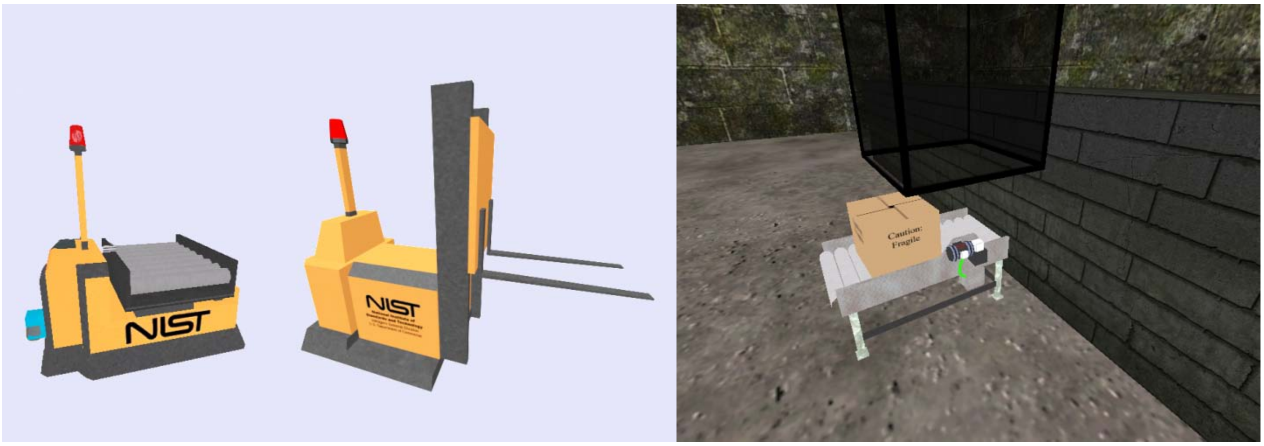

Figure 3: (a) The robot family created for the VMAC competition includes a unit loader and fork lift vehicle. These vehicles are rear-steered Ackerman vehicles.

(b) A conveyor system as well as a "box-chute" was also created for the competition. The box chute generates packages that are dropped onto the conveyor. All of the factory's devices are controlled by the competitors codebase.

Several models have been added to USARSim to support these manufacturing scenarios. This includes the unit loader AGV and fork lift pictured in Figure 3(a) and conveyor and package handling systems. The conveyors, shown in Figure 3(b) exist as stand-alone units and as part of the unit loader. The speed and direction of the conveyors is controlled in the same fashion as the robots. Packages may be requested from the package chute shown in Figure 3(b). These packages have their destination address automatically programmed to either random unloading station locations or preset addresses from an *a priori* file. Automatic logging of package locations takes place to facilitate scoring of the events.

In addition to the factory devices, a sample competition world has been created and posted on the web at http://www.sourceforge.net/projects/usarsim. In addition to the files needed by USARSim to run the map, the package contains *a priori* data in the form of a vector map of obstacles and points-of-interest, and geo-referenced overhead views of the factory floor.

The other part of the provided VMAC infrastructure is the MOAST framework. This framework provides the intelligence for the embodied agent and is fully integrated with the USARSim simulation system. The framework is intended to provide tools to lead a researcher through all of the phases of development and testing of an autonomous agent system. MOAST is comprised of the following components:

1) A reference model architecture that dictates how control responsibilities are divided between modules. More information on the 4D/RCS reference model architecture utilized by MOAST may be found in [7].
2) Communication interface specifications that dictate how and what modules will communicate. More information on the communications systems may be found in [8].
3) Sample control modules for the control of a sample simulated robotic platform. These modules include sensor processing, world modeling, and behavior generation for 4 levels of the hierarchical architecture and provide a complete control system. More information on the control modules may be found in [2].

4) A well defined technique for transitioning from simulated development to real operation. More information may be found in [2].

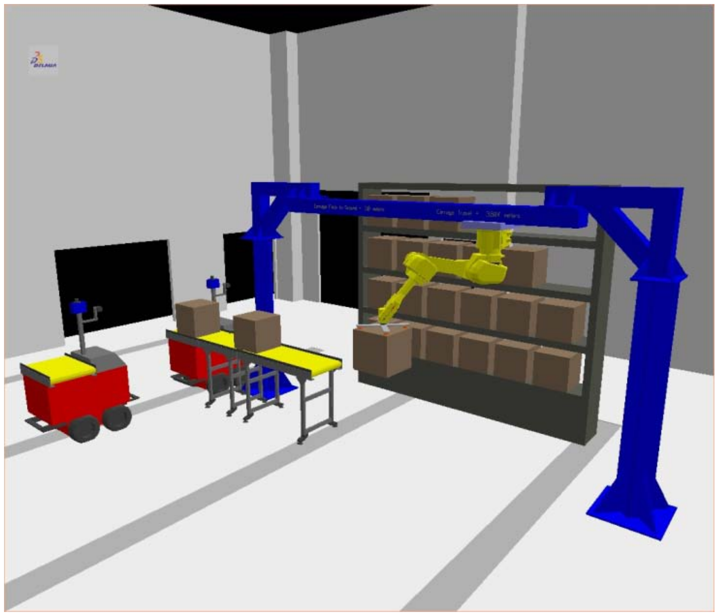

Figure 4: Future vision of VMAC.

Teams competing in VMAC are required to utilize the USARSim system and to support a MOAST compatible communications system for the receipt of commands. However, each team may choose to use as much or as little of the MOAST control framework and architecture as they desire. At the conclusion of each competition, each team's code becomes open source. If that team has utilized MOAST, their code becomes part of the baseline framework.

Last year's competition consisted of discrete events to test path following and docking ability. The winning code is now part of the MOAST repository. In addition, a description of their algorithms was presented at the 2008 PERMIS Workshop. A link to their papers is given here http://www.isd.mel.nist.gov/PerMIS_2008/ (see the online proceedings, under Special Session IV: Results from a Virtual Manufacturing Automation Competition).

2. Virtual Manufacturing Automation Competitions

The 2008 calendar year saw an expansion of the VMAC into both a national and international event. The national event took place at NIST in Gaithersburg, MD April 1-2, 2009 while the international event is currently scheduled to occur in conjunction with the IEEE ICRA conference in Kobe, Japan in May. While the teams are still not ready for a complete comprehensive scenario, progress is being made towards our vision for the future.

2.1. Vision for the Future

The long-term goal of this competition is to present a full factory buffer-zone problem as shown in **Figure 4**. This problem will involve a heterogeneous team of forklifts, robotic arms, and AGVs that will cooperatively clear pallets from a temporary storage location and deliver needed supplies throughout the factory.

The scenario begins with a truck unloading pallets into the buffer zone. When a team of autonomous forklifts (controlled by the competing teams) arrives on the scene, they must move the pallets from the buffer zone to sorted storage shelves located a short distance away. This buffer zone is completely unstructured; there is no map of the area, pallets are located in random locations, and no ground reference system is available. The robotic forklifts must be able to localize themselves and find the correct shelving bins for the pallet contents. Once loaded onto the shelves, the pallet's contents become available for distribution to users in the factory.

The scenario continues with a parts request coming from a factory user. A robotic arm must take a package from the shelves and load it onto a conveyor where an AGV will be able to load the package for delivery. The AGV must then navigate through a dynamic factory environment to deliver the goods. Teams will be presented with *a priori* statistics on the demand for different items and must manage their robotic team so that the shelves remained stocked and parts requests are satisfied. Anticipated challenges include localization, traffic management, driving skills (for docking with pallets and conveyor stations), route planning, and operations in dynamic environments.

2.2. This Year's Competition

This year's competitions present several elemental tests and an overall factory scenario. Three elemental tests are part of the competition.

1) The first elemental test builds upon the docking test from last year's regional competition and will include package handling. Teams have a single vehicle that is pre-located somewhere in a room with a loading station. The team is issued a command over a standard communications channel to begin the mission. Upon receipt of the start command, the team must maneuver their vehicle to the loading conveyor and load a package onto the back of their AGV. The event time ends after the vehicle has docked with the conveyor and loaded a package. At least 5 different starting locations are tested to improve statistical significance. Points are awarded based on placement in each round with the team with the largest number of points being deemed "best-in-class" docking.
2) The second elemental test evaluates a simple traffic scenario. This scenario places three vehicles in the world. The team will be issued a start-of-mission command that will contain a goal location for each of the three vehicles. Time for this test will begin with the receipt of the start command and will end when all of the vehicles have reached their goal locations. At least 5 different starting/goal locations will be tested to improve statistical significance. Points will be awarded based on placement in each round. The team with the largest number of points will be deemed "best-in-class" traffic management.
3) The final elemental test will measure a team's ability to cope with unknowns in the environment. A single vehicle is placed in the world and given a goal location. For this test, the *a priori* data provided the teams will no longer be guaranteed to be correct. Paths may have become blocked, and obstacles may have been dropped on the floor. Collisions will eliminate the team from the given round. The team with the largest number of points will be deemed "best-in-class" for environmental sensing.

In addition to the elemental tests, each team will have the opportunity to participate in an end-to-end scenario. For this scenario, a team of unit loaders is tasked with transporting packages from a loading station to several different unloading stations. The unit loaders are required to dock with the loading/unloading stations and interact with a conveyor system to load packages. The vehicle will then need to determine the package's destination (through an RFID tag), and transport the package to the correct unloading station. Following our vision for the future, this year's challenges include autonomous vehicle control, path planning, and traffic management. Multiple paths exist from the loading station to the unloading station, and there is a trade-off between path length and path traversal difficulty.

For the competition, teams are encouraged to participate in as many of the elemental tests as possible as well as the full scenario. In order to make participation possible for small teams or teams with limited resources, partial participation (e.g. only competing in selected elemental tests) and remote participation is possible. In addition, the map that was used for the national event was the same as the practice map that had previous been posted on the web at http://sourceforge.net/projects/usarsim.

3. Competition Results

This year's national competition took place on April 1, 2009 at the NIST Gaithersburg, MD campus. Hood College of Frederick, MD participated on site while the University of California, Merced participated remotely. Both teams utilized a modified version of the MOAST control framework as their robot controller and competed in the docking elemental test. Hood College also participated in the end-to-end scenario.

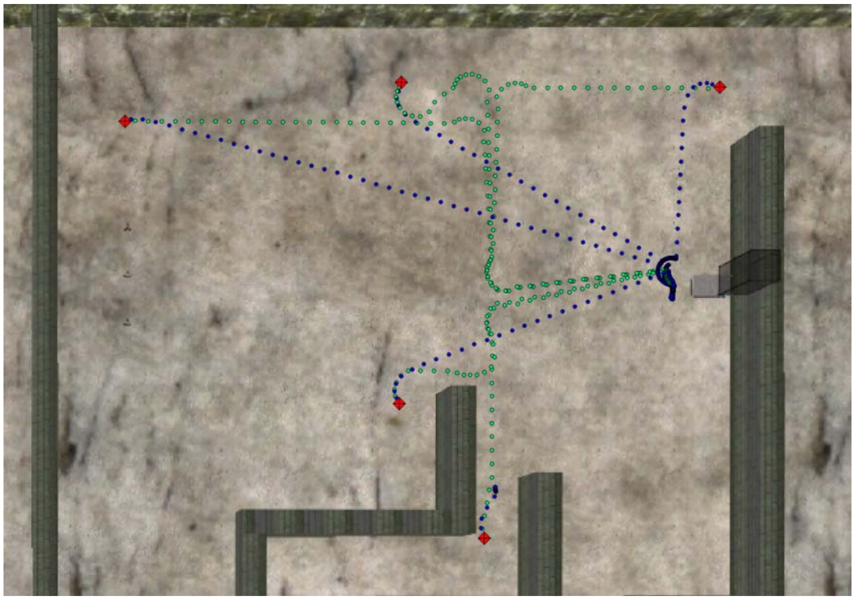

Figure 5: Docking runs from the 2009 VMAC national event. Team ‘A’ runs are in green while Team ‘B’ runs are in blue. The starting locations are marked by the red squares and the goal is the loading station on the right-hand side of the picture.

3.1. Docking Elemental Test

For the docking elemental test, each team was provided with 5 different starting locations and was required to dock with the conveyor. Each team then had to control the factory equipment to successfully load a package. 1 point was awarded for successful completion of the docking procedure, and an additional point was awarded for having the fastest completion time. As may be seen from
Figure **5**, the two teams employed different strategies for accomplishing the mission. Team ‘A’ ran in a direct path to the loading station, while team ‘B’ always navigated to a central point from which they knew of a correct docking maneuver. Team ‘A’ was able to successfully dock from all of the tested positions, while team ‘B’ failed from one of the starting points. After all 5 runs were completed; both teams were tied with 7 points each.

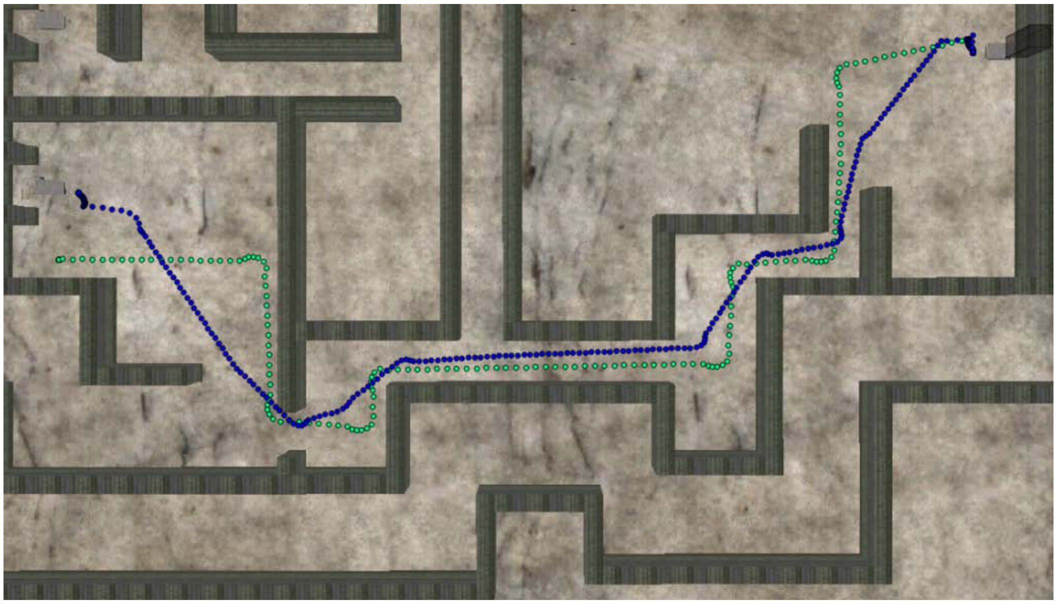

Figure 6: Vehicle's navigating maze area.

3.2. Traffic Management and Dynamic Environment Elemental Tests

None of the competing teams was prepared to participate in the traffic management or dynamic environment tests at the national competition. However, code improvements are currently being made that should make participation possible in the 2009 international event.

3.3. End-to-End Run

For the end-to-end run, Hood College was able to successfully deliver a package with a single vehicle. UC Merced had not yet finished integrating an end-to-end solution. However, we were able to run both systems in the maze and observe the difference in their operation through the maze. The data logging facility also includes the ability to demonstrate real-time playback of the data. This will be instrumental in comparing results once teams are able to control the full contingent of three vehicles.

Figure 7: VMAC code running on NIST's surrogate unit loader AGV.

3.4. Moving to Real Vehicles

One of the main focuses of the competition is the ability to move code from the simulation system to real platforms. It is a strongly-held belief amongst the competitors that simulation should not be an end onto itself. Simulation should be used to develop and debug algorithms, which should then be run on real hardware. The framework adopted by VMAC allows for a seamless transition from the simulation to real platforms that support the Player interface (see http://sourceforge.net/projects/playerstage for more information). This was demonstrated this year with NIST's surrogate unit loader AGV (actually an ATRV robot with a conveyor system). The code from Hood College was transferred to the robot without any algorithm changes taking place. The code was then run on the vehicle. The surrogate unit loader was able to successfully pick-up and deliver a package in the NIST test facility. The entire transition from simulation to real implementation was performed in under two hours. This is shown in Figure 7.

4. Beyond the Competition …

By incrementally increasing the challenges that are faced by teams, we are hoping to improve the capabilities of both the university participants and eventual technology customers. The metrics-driven competition model allows us to measure the advancements in the various technologies comprising the AGV control system; thus helping the community gauge as well as target progress. It is our belief that these competitions will serve as a model for establishing a university-community focused on a real-world practical problem.

From competition debriefings, we found that the universities were pleased with the objectives and elements of the competition. However, they expressed frustration over the large learning curve of getting the provided control system up and running. Since lowering entry barriers is a major objective of this competition, in-depth conversations were held to discover how the learning curve may be shortened. As a result of these conversations, a new novice API is under development that will allow novice programmers to quickly get a robot up and running in as few as five lines of code.

The seeds from these competitions are already bearing fruit. Several additional universities have expressed interest in participating in the international event and some are even planning courses based on the material and expertise that they have gained as a direct result of their participation in this competition series. The continued operation of this competition will facilitate expanding the user base and building a self-sustaining community that is able to pool resources and create improvements to the manufacturing control and simulation systems.

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