PATH TO SUCCESS: AN ANALYSIS OF 2016 INTELLIGENT GROUND VEHICLE COMPETITION (IGVC) AUTONOMOUS VEHICLE DESIGN AND IMPLEMENTATION

Authors: Andrew Kosinski (Mechanical Engineer, US Army TARDEC, IGVC 2016 Director), Jerry Lane (GLS&T, IGVC Co-Founder), KaC Cheok (IGVC Co-Founder), Bernie Theisen (US Army TARDEC, IGVC Co-Chair)

Section 1. IGVC 2016 Abstract:

Figure 1. IGVC 2015 Opening Ceremony.

The IGVC is a college level autonomous unmanned ground vehicle (UGV) competition that encompasses a wide variety of engineering professions – mechanical, electrical, computer engineering and computer science. It requires engineering students from these varied professions to collaborate in order to develop a truly integrated engineering product, a fully autonomous UGV.

Drilling down further, students must overcome a large variety of engineering technical challenges in control theory, power requirements/distribution (battery selection, etc.), cognition, machine vision (visual/stereo cameras, LIDAR, etc.), vehicle electronics, mobile platform fundamentals, vehicle electronics, sensors, systems integration, vehicle steering, fault tolerance/redundancy, noise filtering, PCB design/analysis/selection, vehicle engineering analysis, design, fabrication, field testing, lane-following, avoiding obstacles, operation without human intervention, detection and navigation of various obstacles (slopes, potholes, flags (detection and right/left travel logic), switchbacks, center islands), vehicle simulation/virtual evaluation, natural environments (grass, mud, rain, sun), Global Positioning System/waypoint navigation, safety design, etc. As can be seen, it is an excellent college level test to develop college level engineers and prepare them for their future engineering jobs.

There are three sub-competitions within IGVC 2016, the Design Competition, Auto-Nav Challenge and Interoperability Profile (IOP) Challenge. The Design Competition challenges students to document their vehicle development by creating a design report, followed by an in-person presentation to the design judges during the actual IGVC 2016 event, including a vehicle examination by the judges. The Auto-Nav Challenge is the main challenge, which consists of two outdoor obstacle courses (Advanced and Basic course), requiring the UGVs to perform full autonomous operation/navigation throughout. The IOP Challenge encourages students to make their vehicles more interoperable, by requiring development of a Joint Architecture for Unmanned Systems (JAUS) compliant UGV, which is the architecture current military robots are being designed to. Programs such as the Robotic Operating System (ROS) are used by teams for designing/implementing software code, allowing for easier integration of new sensors and to help ensure commonality among the UGVs.

Section 2.1. Technical Challenge #1 – Frame/Suspension/Mast Selection/Design:

Some of the engineering technical challenges mentioned above will now be explored in greater depth. Mechanical engineering challenges including designing/calculating appropriate placement of components to ensure an optimal vehicle center of gravity, as speed is a driving requirement for placing well in the Auto-Nav Challenge.

UGV material selection must be performed, with teams tending to use aluminum for most frame components due to its low weight and ease of assembly using cheap, prefabricated aluminum components, such as 80/20 T-slotted aluminum framing.

This type of selection also has the benefit of allowing for easy swap out of components and simplified/quick vehicle frame reconfiguration. An additional benefit to 80/20 T-slotted aluminum framing is that welding can be avoided. Optimal frame selection/mechanical design can be assisted through the use of CAD software.

Suspension systems allowing for better component isolation to vibration/forces are usually included in the vehicles, typically centering on the use of traditional struts, springs, etc. Masts are usually installed for mounting of mono/stereo cameras to give a high point of view. Students usually use predrilled aluminum extrusion for easy/rapid adjustment of camera height.

Some teams use prefabricated frames/suspension systems, such as using electric wheelchairs. This has the advantage of reducing frame/suspension development time and testing, freeing up time for other IGVC vehicle work. Another benefit is taking advantage of a proven vehicle in terms of reliability, durability, etc. Below is a CAD rendering of the 2015 Oakland University team's vehicle, using an electric wheelchair as the base:

Figure 2/3. CAD Drawing and Picture of 2015 Oakland University Team's Vehicle[3].

Section 2.2. Technical Challenge #2 – Vehicle Power/Battery/PCB Analysis/Selection/Fabrication:

Motors must be selected, with students usually performing basic torque analysis to ensure the vehicle is capable of delivering an adequate overall vehicle speed, as well as being able to tackle the likely obstacles/environment the vehicle will face during the Auto-Nav completion, which as mentioned above can consist of slopes (up to 15° in Auto-Nav Challenge), potholes, muddy ground, grass/dirt, etc.

A typical torque analysis utilizes parameters such as vehicle weight, coefficient of friction, # of motors, wheel diameter, etc. Free-body diagrams can be used for necessary force calculations, such as given below from the 2015 CSUN Design Report[1]:

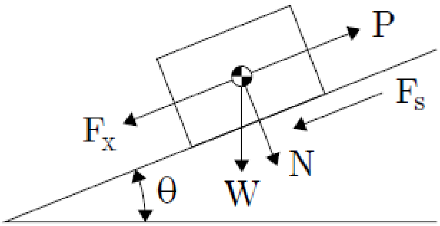


Figure 4. 2015 CSUN Vehicle Free-body Diagram.

The various vehicle motors/sensors/circuit boards/components all have unique power draws at a variety of voltages, making power selection and distribution critical. Virtually all teams now use batteries as their vehicle's power source, although in the past fuel cells and combustion engines were used. Also, solar panels have been used by the US Naval Academy team in recent years to supplement battery power[4]. Battery technology has obviously advanced significantly over recent years, giving batteries a good form factor to power ratio. Lithium Ion and Lithium Polymer batteries are popular among teams, although lead acid are also still used.

Below are two examples of the various common components requiring power in an IGVC vehicle, which are from the 2015 CSUN Design Report[1] and the 2015 UNSW Design Report[2]:

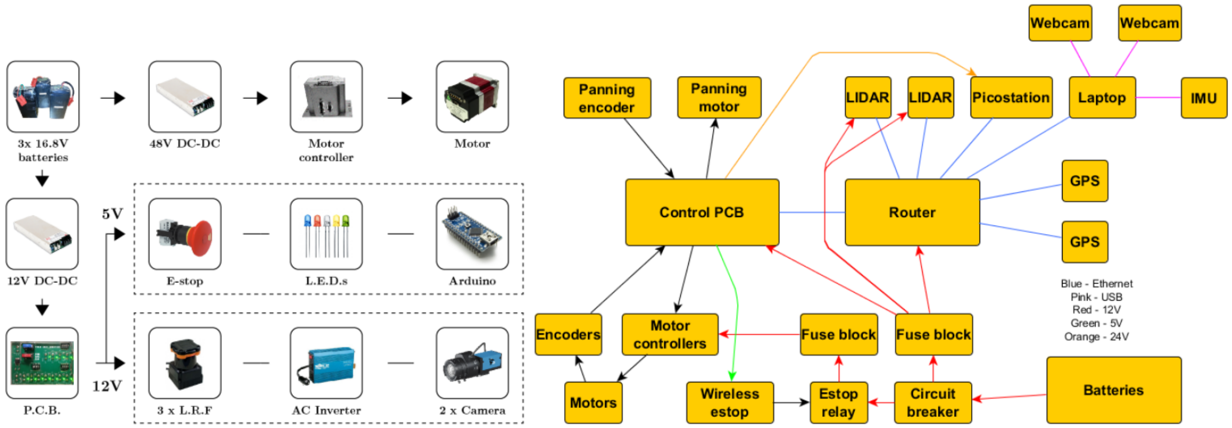


Figure 5/6. 2015 CSUN/UNSW vehicle components, respectively.

As shown in the above pictures, and as mentioned partially in the beginning, common components include sensors (cameras and LADARs), PCBs, power converters/inverters, motor controllers, motors, e-stops and CPUs. Typical voltage requirements, as shown above, tend to be 5V, 12V and the motor's voltage. Clearly battery selection is of upmost importance, as if even one of these components receives too little power, the whole robot can become significantly degraded, if not entirely.

As mentioned above, battery selection is primarily dictated by overall power requirements of the various components, with typically the majority of the power draw coming from the drive motors. IGVC teams normally use wattmeters to determine the power draw of components at nominal and extreme load operations (extreme load usually equates to the vehicle operating at full desired course speed/incline).

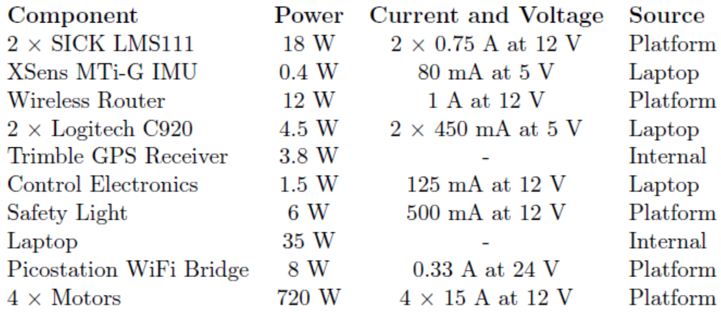
Below is an example table of power draws determined by the 2015 CSUN team, when their vehicle was operating at normal load (1mph) and extreme load (6.8mph):

Table 1. 2015 CSUN Vehicle Power Draw Data[1].

Type of Load	Normal Load	Extreme Load
Total base load	177	177
Transient motor load	154	910
Total load	331	1087
Total at 88% DC/DC efficiency	376	1235

Below are the vehicle component power draws for the 2015 UNSW vehicle:

Table 2. 2015 UNSW Power Draws of Vehicle Components[2].



Component	Power	Current and Voltage	Source
2 × SICK LMS111	18 W	2 × 0.75 A at 12 V	Platform
XSens MTi-G IMU	0.4 W	80 mA at 5 V	Laptop
Wireless Router	12 W	1 A at 12 V	Platform
2 × Logitech C920	4.5 W	2 × 450 mA at 5 V	Laptop
Trimble GPS Receiver	3.8 W	-	Internal
Control Electronics	1.5 W	125 mA at 12 V	Laptop
Safety Light	6 W	500 mA at 12 V	Platform
Laptop	35 W	-	Internal
Picostation WiFi Bridge	8 W	0.33 A at 24 V	Platform
4 × Motors	720 W	4 × 15 A at 12 V	Platform

From the data gathered from measuring power draws from the various components during the battery selection phase, necessary power distribution to the various components can be determined, normally then requiring the design of a printed circuit board (PCB). There are many CAD and PCB programs that can be used to create a virtual PCB, which can then be sent off for official manufacture.

Below is the virtual PCB side-by-side with the actual PCB created from this template for the 2015 CSUN vehicle:

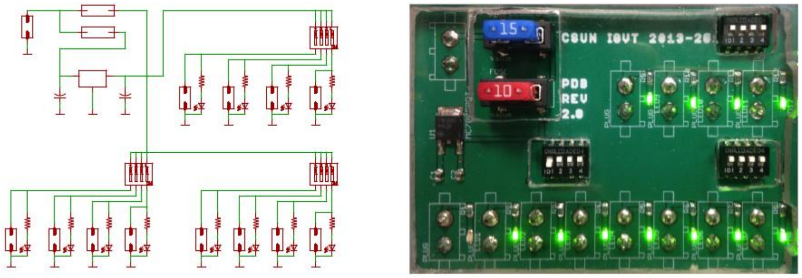


Figure 7. 2015 CSUN Virtual/Actual Main PCB[1].

Section 2.3. Technical Challenge #3 – Vehicle E-Stop/Safety Considerations/Design/Implementation:

Emergency stops are a required component of every IGVC UGV. Without a physical e-stop on the vehicle and a wireless e-stop system (typical setup is a transmitter held by an IGVC field judge with an e-stop button on it, which typically triggers a vehicle circuit board with the singular function of safely powering down the UGV), the vehicle is not allowed to run the Auto-Nav Challenge. Normally the e-stop functions by killing power to the motor controllers.

Below is a picture of a typical e-stop vehicle installation, from the 2015 Oakland University team:

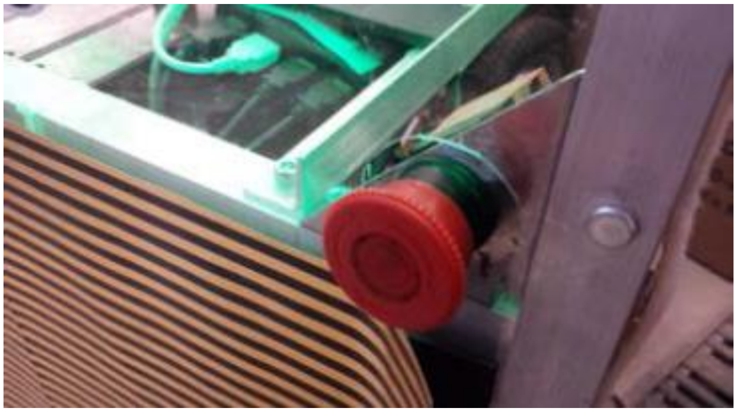


Figure 8. 2015 Oakland University Team's Vehicle Mounted E-Stop[3].

The Oakland University team employed the additional safety ability of having the drive control system automatically turn off the motors if it fails to receive commands from the computer or wireless joystick after 200ms.

Section 2.4. Technical Challenge #4 – Vehicle Machine Vision – Sensor Selection/Processing/Implementation:

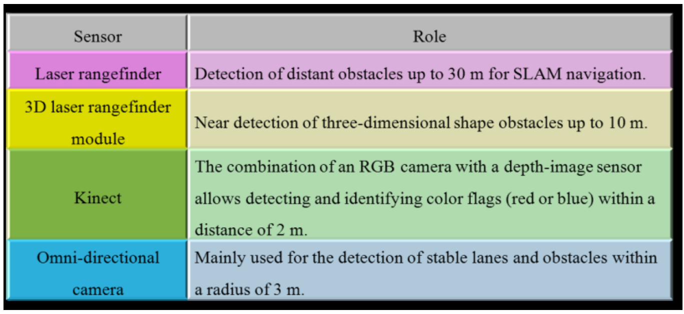
Vehicle machine vision is a huge part of a successful IGVC vehicle, as the vehicle is completely on its own while operating in the Auto-Nav Challenge. As mentioned above, teams normally use mono/stereo cameras and LADAR. Component redundancy is important, even more-so with regards to sensors, with some teams adding multiple cameras for redundancy as well as to increase the sensors' field of view for detection. Teams have also installed planar LADARs on pan-tilt assemblies to allow for 3-D sweeping detection. 3-D sweeping is especially important for detecting negative obstacles, like potholes.

A significant sensor challenge is not just processing and analyzing a sensor's data feed, but then integrating it with the other vehicle sensors to build a coherent world map of the vehicle's environment. Normally simultaneous localization and mapping (SLAM) algorithms are used for this purpose. SLAM also serves as a good redundancy to the data pulled from the vehicle's high precision differential GPS.

This then immediately ties into requiring robust software coding, building in a comprehensive ruleset to be able to segment out irrelevant data and filter noise, as well as segment and recognize important parts of the world map corresponding to obstacles (barrels, potholes, ramps) and other items of interest (flags, spray painted course boundary lines, etc.). In addition to categorizing these items, there needs to be further logic with regards to flags and spray painted course lines.

The logic for spray painted lines is straightforward, to have the vehicle stay between the two boundary lines. The logic for flags is more involved, requiring the machine vision system to first not only detect the flags, but accurately determine their color (red or blue), and then after knowing the color, program the vehicle to stay to the left of the red flags and to the right of the blue flags.

The accurate detection of flags was a challenge to many teams since their introduction a few years ago (mainly due to the small size). It was only within the last couple years that a vehicle not only successfully detected the flags, but also correctly navigated to the left of red flags and to the right of blue flags, in order to complete the entire Advanced Auto-Nav Challenge. One innovative sensor that was employed specifically to deal with the new flags was the Xbox Kinect device, which is equipped with a RGB camera and depth sensor. The 2012 Hosei team chose to use the Kinect, due to its likely ability to recognize the shape and color of a flag simultaneously, having a sufficient resolution (640x480 pixels) to allow for expected recognition within 2 meters. The 2012 Hosei team also utilized a laser range finder, 3-D sweeping laser range finder and omnidirectional camera for overall vehicle detection/identification performance. Below is a table and picture of the role of each 2012 Hosei sensor and each sensor's field of view:



Sensor	Role
Laser rangefinder	Detection of distant obstacles up to 30 m for SLAM navigation.
3D laser rangefinder module	Near detection of three-dimensional shape obstacles up to 10 m.
Kinect	The combination of an RGB camera with a depth-image sensor allows detecting and identifying color flags (red or blue) within a distance of 2 m.
Omni-directional camera	Mainly used for the detection of stable lanes and obstacles within a radius of 3 m.

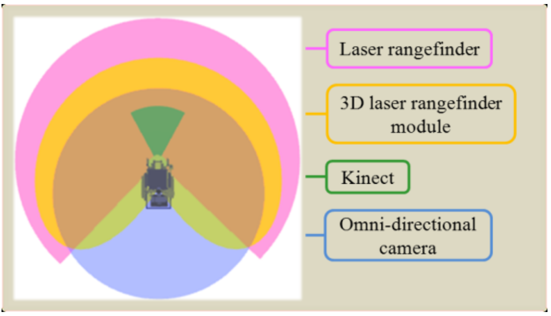


Table 3/Figure 9. 2012 Hosei Team's Sensor Roles and Fields of View[5].

Sensor noise can become extremely problematic, requiring implementation of additional processing techniques, such as the 2015 Oakland University team's application of an Artificial Neural Network (ANN) to assist in the determination of the white course boundary lines. Using self-learning approaches can be very helpful in situations like this, where hard coding white line extraction algorithms that will be applicable in real-life IGVC implementation become challenging. The ANN white line detection process the 2015 Oakland University team used is characterized below:

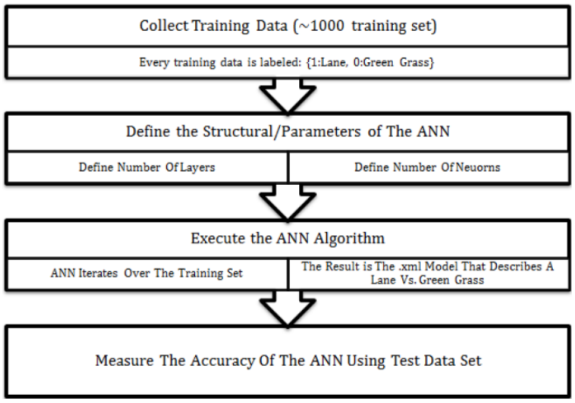


Figure 10. 2015 Oakland University Team's ANN White Line Detection Process[3].

See below for layout examples of the Basic and Advanced Auto-Nav Challenge course:

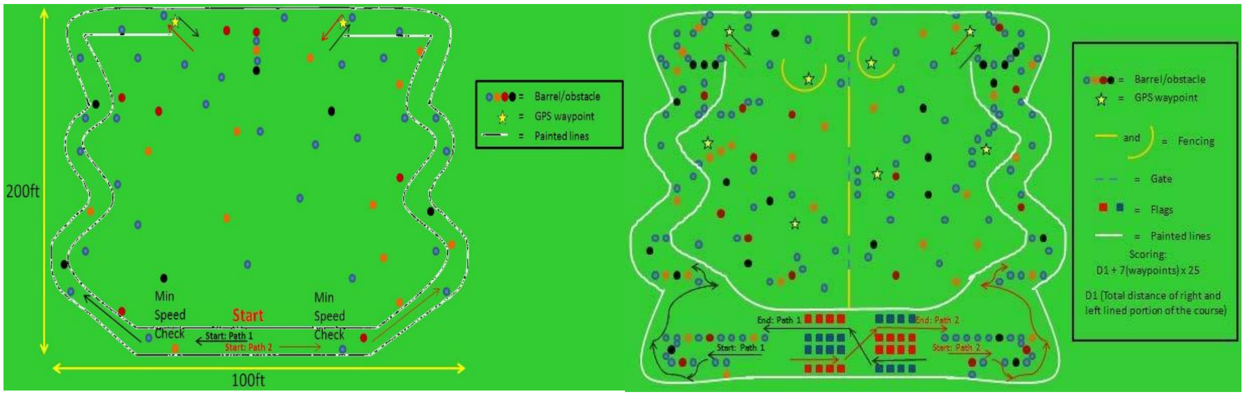


Figure 11. Sketch of Potential 2016 IGVC Basic/Advanced Auto-Nav course layout.

Figure 12. Pictures of 2015 Auto-Nav Challenge Course.

Section 2.5. Technical Challenge #5 – Vehicle Simulation/Real-Life Testing:

Testing of the vehicle is critical and it can take the form of real-life testing and/or simulation. See below for a mock IGVC course created by the 2015 UNSW team for vehicle testing/evaluation:

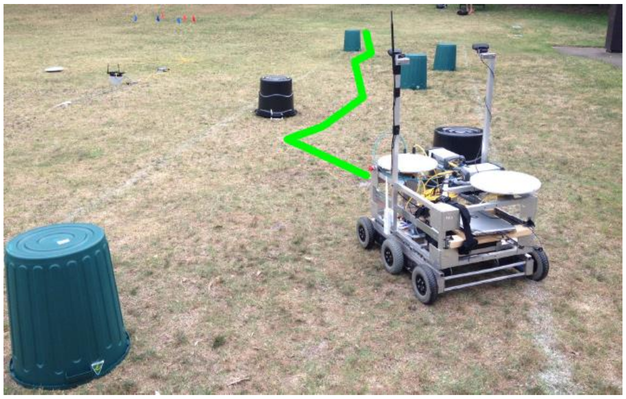


Figure 13. 2015 UNSW Team's Mock IGVC Auto-Nav Challenge Course[2].

An obvious advantage of simulation over real-life testing is that the vehicle can be worked on while evaluating its (virtual) performance on a computer. An obvious drawback to simulations is that it is only as good as the input data, simplifying assumptions, etc. Another advantage of a simulation is that the (virtual) vehicle can be evaluated many times faster than real-time.

The 2015 UNSW team's simulation environment allowed for the simulation to be run up to 5 times faster than real-time and in parallel. The advantages of this can be extreme, assuming wise creation of the simulation environment as a whole and informed determination of the necessary input data, simplifying assumptions, etc., to ensure a highly accurate representation of the real-life vehicle conditions/environment/operations. This can allow for a huge scaling in the amount of vehicle testing within a timeframe, which can greatly improve overall vehicle operation/performance in future real-life testing and at the actual IGVC competition.

Obviously huge amounts of data are generated from these virtual vehicle runs, which then necessitates quick/accurate analysis in order to be useful. For this purpose, the 2015 UNSW team developed and incorporated several tools to "automatically analyze and collect statistics regarding the performance in a simulated run of the competition. These statistics, which include average speed, localization error, and proximity to obstacles, allow for quick tuning and verification of parameters to determine which combination of these parameters optimizes the performance of the system as a whole."[2]

The 2015 CSUN team developed their simulation program using LabVIEW. As they state, "The simulation was developed as a method to allow testing of new codes without endangering the vehicle with a previously untested code, which may have bugs that create unsafe conditions for El Toro...Virtual LRF (laser range finder) data is created, while inducing specified levels of Gaussian white noise to more realistically represent the stream of data that would come from the sensors. This allows the vehicle to choose different paths each time it navigates through the simulation. The simulated data gathered by the LRF and compass is passed to the navigation and system integration code, allowing the vehicle to run autonomously."[1]

CSUN's computer generated IGVC map used for their simulations can be seen below:

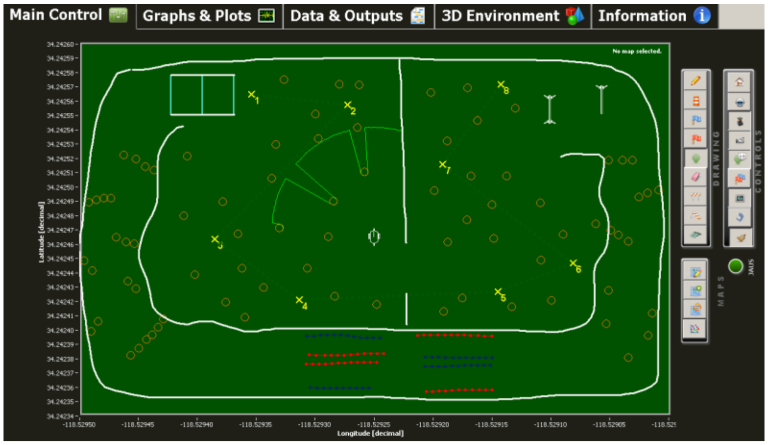


Figure 14. 2015 CSUN Team's Simulation of the IGVC Auto-Nav Challenge Course[1].

The real-life improvements of a system, such as for these IGVC vehicles, from utilizing effective simulations cannot be overstated, especially with the growing virtual toolset for improved simulation, analysis and optimization of real-life system performance. Such toolsets include optimization routines such as neural networks and evolutionary systems, as well as deep learning, which was displayed in a limited, though dramatic degree, with regards to a virtual tool (deep learning computer program AlphaGo) quickly optimizing its performance of the game of GO, beating arguably the best GO player in the world, Lee Sedol, well ahead of the projected timeframe, including demonstrating a vast level of improvement within a short timeframe (going from beating European Go champion Fan Hui (2-dan) in October 2015 to beating Lee Sedol (9-dan) in March 2016).

Section 3. IGVC 2015 Competition Results:

Grand Award

Figure 15. 2015 California State University, Northridge 1st Place Team.

1. California State University, Northridge Team: El Toro
Grand Award Points: 64
Award: Lescoe Cup

2. University of New South Wales Team: Pepper
Grand Award Points: 60
Award: Lescoe Trophy

3. École de technologie supérieure Team: CAPRA6
Grand Award Points: 24
Award: Lescoe Award

3. Embry Riddle Aeronautical University Team: Zero2
Grand Award Points: 24

Award: Lescoe Award

3. Oakland University Grand Award Points: 24 Award: Lescoe Award	Team: Mantis
6. Lawrence Technological University Points: 20	Team: Bigfoot
7. University of Michigan-Dearborn Points: 16	Team: OHM 3.0
7. Trinity College Points: 16	Team: Q
9. United States Naval Academy Points: 12	Team: Robogoat
10. University of British Columbia Points: 10	Team: Snowflake
11. Bluefield State College Points: 8	Team: Apollo
11. Hosei University Points: 8	Team: Orange2015

Advanced Auto-Nav Challenge

1. University of New South Wales Distance: 1032 Time: 3:52 Award: $5,000 Grand Award Points: 48	Team: Pepper
2. California State University-Northridge Distance: 1032 Time: 10:00 Award: $4,000 Grand Award Points: 40	Team: El Toro
3. University of Michigan-Dearborn Distance: 756 Time: 6:46 Award: $1,000 Grand Award Points: 16	Team: OHM 3.0
4. United States Naval Academy Distance: 440 Time: 8:55 Award: $750 Grand Award Points: 12	Team: Robogoat
5. Ecole de Technologie Superieure Distance: 254 Time: 5:59	Team: CAPRA6

Award: $500
Grand Award Points: 8

6. Oakland University Team: Mantis
Distance: 244
Time: 1:47
Award: $250
Grand Award Points: 4

7. Lawrence Technological University Team: Bigfoot
Distance: 125
Time: 1:19

Basic Auto-Nav Challenge
1. University of New South Wales Team: Pepper
Distance: 510
Time: 1:27
Award: $2,500

2. California State University-Northridge Team: El Toro
Distance: 510
Time: 1:58
Award: $2,000

3. Oakland University Team: Mantis
Distance: 510
Time: 2:34
Award: $1,500

4. University of Michigan-Dearborn Team: OHM 3.0
Distance: 510
Time: 3:26
Award: $1,000

5. United States Naval Academy Team: Robogoat
Distance: 510
Time: 3:33
Award: $750

6. Ecole de Technologie Superieure Team: CAPRA6
Distance: 510
Time: 4:28
Award: $500

7. Lawrence Technological University Team: Bigfoot
Distance: 510
Time: 5:00

8. Embry-Riddle Aeronautical University Team: Zero2
Distance: 430
Time: 5:00

9. Trinity College Team: Q
Distance: 290
Time: 5:00

10. Hosei University Team: Orange2015

Distance: 284
Time: 4:11

11. Université de Moncton Team: BreakPoint
Distance: 157
Time: 2:45

12. University of Detroit Mercy Team: Thor Pro
Distance: 85
Time: 1:36

13. Bluefield State College Team: Apollo
Distance: 60
Time: 0:19

Design Competition Finalists

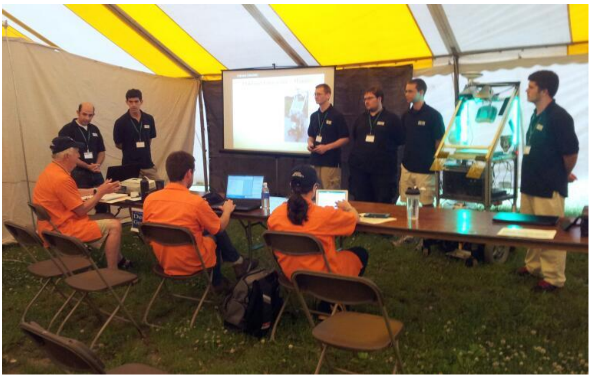


Figure 16. 2015 Design Presentation.

1. Embry-Riddle Aeronautical University Team: Zero2
Score: 432.22/480
Award: $3000
Grand Award Points: 24

2. Oakland University Team: Mantis
Score: 408.11/480
Award: $2000
Grand Award Points: 20

3. École de technologie supérieure Team: CAPRA6
Score: 402.78/480
Award: $1000
Grand Award Points: 16

4. University of British Columbia Team: Snowflake
Score: 394.78/480
Award: $300
Grand Award Points: 6

5. Bluefield State College Team: Apollo
Score: 393.44/480
Award: $500
Grand Award Points: 8

6. Hosei University Team: Orange2015
Score: 388.44/480

Award: $250
Grand Award Points: 4

IOP Challenge

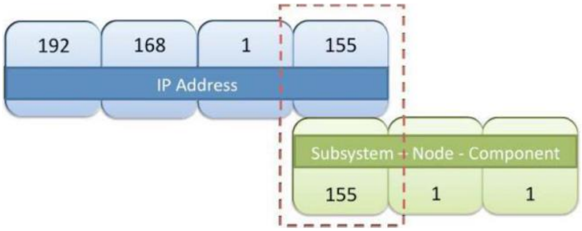


Figure 17. IOP Challenge IP and JAUS ID Assignment Example.

1. California State University, Northridge Team: El Toro
Award: $3000
Grand Award Points: 24

2. Lawrence Technological University Team: Bigfoot
Award: $2000
Grand Award Points: 20

3. Trinity College Team: Q
Award: $1000
Grand Award Points: 16

4. University of New South Wales Team: Pepper
Award: $750
Grand Award Points: 12

5. University of British Columbia Team: Snowflake
Award: $200
Grand Award Points: 4

6. Hosei University Team: Orange2015
Award: $250
Grand Award Points: 4

Rookie of the Year Award

Figure 18. 2015 University of New South Wales 2nd Place Team.

University of New South Wales Team: Pepper
Award: $1000

Historical Results – Final Team Rankings (2010-2014):

2014:

1. Oakland University
Team: Mantis
Points: 64
Award: Lescoe Cup

2. California State University, Northridge
Team: Vader
Points: 36
Award: Lescoe Trophy

3. Hosei University
Team: Orange2014
Points: 28
Award: Lescoe Award

4. University of Michigan, Dearborn
Team: OHM 2.0
Points: 20

5. Embry-Riddle Aeronautical University
Team: Zero
Points: 18

6. Trinity College
Team: Q14
Points: 10

7. Lawrence Technological University
Team: iWheels 2
Points: 8

7. University of Illinois at Chicago
Team: EDT-Scipio
Points: 8

9. Yale University
Team: Armstrong
Points: 6

10. The Citadel
Team: Spike
Points: 4

11. Bob Jones University
Team: Isaiah
Points: 2

2013:

1. Oakland University
Team: Replicant
Points: 36
Award: Lescoe Cup

2. Hosei University
Team: Orange 2013
Points: 24
Award: Lescoe Trophy

2. California State University, Northridge
Team: Scorpion
Points: 24
Award: Lescoe Trophy

4. United States Naval Academy
Team: Robogoat
Points: 20

5. Embry-Riddle Aeronautical University
Team: Alvin
Points: 14

6. Embry-Riddle Aeronautical University
Team: Mollebot
Points: 12

7. University of Detroit Mercy
Team: Revenant
Points: 10

8. University of Illinois at Chicago
Team: EDT-Scipio
Points: 8

9. University of Central Florida
Team: Automaton
Points: 6

10. Lawrence Technological University
Team: iWheels
Points: 4

10. Miami University
Team: Redblade
Points: 4

10. École de technologie supérieure
Team: Capra6
Points: 4

13. Dalhousie University
Team: Segfault
Points: 2

2012:

1. California State University, Northridge
Team: Red Raven 2.0
Points: 60

Award: Lescoe Cup

2. Hosei University
Team: Active 2012
Points: 50
Award: Lescoe Trophy

3. Oakland University
Team: Botzilla
Points: 40
Award: Lescoe Award

3. United States Naval Academy
Team: Robogoat
Points: 40
Award: Lescoe Award

5. Embry Riddle Aeronautical University
Team: Reagle V
Points: 32

6. Lawrence Technological University
Team: vuLTUre 2
Points: 28

7. University of Detroit Mercy
Team: BAZINGA!
Points: 24

8. Michigan Technological University
Team: Bishop
Points: 12

9. Rutgers University
Team: Navi
Points: 10

10. California State University, Northridge
Team: LINJA
Points: 8

10. Georgia Tech
Team: Roxii
Points: 8

12. Embry Riddle Aeronautical University
Team: Molle
Points: 6

13. University of Wisconsin, Madison
Team: Singularity
Points: 4

2011:

1. California State University - Northridge
Team: Red Raven
Points: 72
Award: Lescoe Cup

2. University of Central Florida
Team: Automaton
Points: 54
Award: Lescoe Trophy

3. Hosei University
Team: Active 2011
Points: 48
Award: Lescoe Award

3. University of Delaware
Team: Warthog
Points: 48
Award: Lescoe Award

4. Oakland University
Team: Botzilla
Points: 32

4. University of Waterloo
Team: Indrik
Points: 32

5. Georgia Institute of Technology
Team: Roxi
Points: 16

6. Trinity College
Team: Q
Points: 14

6. Embry-Riddle Aeronautical University
Team: Reagle
Points: 14

7. York College of Pennsylvania
Team: Sparta
Points: 12

8. Embry-Riddle Aeronautical University
Team: Molle Bot
Points: 8

8. University of Wisconsin - Madison
Team: Singularity
Points: 8

9. Lawrence Technological University
Team: vuLTUre
Points: 6

2010:

1. University of Detroit Mercy
Team: Cerberus
Points: 108
Award: Lescoe Cup

2. Hosei University
Team: Orange 2010
Points: 70
Award: Lescoe Trophy

3. Trinity College
Team: Q
Points: 40
Award: Lescoe Award

4. University of Delaware
Team: Warthog
Points: 34

5. California State University - Northridge
Team: NorMAN Jr.
Points: 32

6. The City College of New York
Team: City Alien
Points: 24

6. University of Massachusetts - Lowell
Team: MCP III.5
Points: 24

7. Princeton University
Team: Phobetor
Points: 20

8. Franklin W. Olin College of Engineering
Team: Athena
Points: 16

8. Lawrence Technological University
Team: Culture Shock II
Points: 16

9. University of Wisconsin - Madison
Team: Paradroid
Points: 12

10. Case Western Reserve University
Team: Jinx
Points: 8

11. Georgia Institute of Technology
Team: Jeanni
Points: 4

11. Missouri University of Science and Technology
Team: Aluminator
Points: 4

11. Rochester Institute of Technology
Team: AMOS III
Points: 4

12. Michigan Technological University
Team: Hi-Techie
Points: 2

Appendix

1. California State University-Northridge (CSUN) Design Report. 2015. http://www.igvc.org/design/2015/4.pdf.
2. University of New South Wales (UNSW) Design Report. 2015. http://www.igvc.org/design/2015/24.pdf.
3. Oakland University Design Report. 2015. http://www.igvc.org/design/2015/16.pdf.
4. United States Naval Academy (USNA) Design Report. 2014. http://www.igvc.org/design/2014/30.pdf.
5. Hosei University Design Report. 2012. http://www.igvc.org/design/2012/Hosei%20University.pdf.