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THE SYNERGISTIC COMBINATION OF RESEARCH, EDUCATION, AND INTERNATIONAL ROBOT COMPETITIONS THROUGH THE DEVELOPMENT OF A HUMANOID ROBOT

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ABSTRACT
This paper presents our experience of how a graduate research project on humanoid robots was successfully fused together with undergraduate design projects, which also resulted in successful spin-off teams for international robot competitions. The research portion of the project and some of the technical details of the development of the humanoid robot is presented, followed by discussions of the motivation, operation, results, and lessons learned for the organization of the undergraduate senior capstone design projects and the competition, including the roles of the graduate students as mentors. Our approach resulted in not only a successful sponsored research program, but also a number of awards in design competitions, international robot competitions, and best paper awards.

INTRODUCTION
This paper will show how graduate research on humanoid robotics can be fused together with undergraduate senior design projects, which also resulted in a side project of an international autonomous robotics competition. This paper will present what went into the research, senior design project, and competition including organization, operation, etc, as well as why and lessons learned. Additionally this paper will present some of the development of robot itself including: mechatronics, prototype development, mechanical design, etc. The research, senior design project, and autonomous robot competition discussed in this paper uses the (DARwIn Dynamic Anthropomorphic Robot with Intelligence) series robot-a family of humanoid robots capable of bipedal walking and performing human-like motions. Developed at the Robotics and Mechanisms Laboratory (RoMeLa) at Virginia Tech, DARwIn is a research platform for studying robot locomotion and was also the base platform for Virginia Tech's first entry to the humanoid division of 2007 RoboCup, an international autonomous robot soccer competition [1]. The 600 mm tall, 4 Kg robot (the latest version of DARwIn) has 21 degrees-of-freedom (DOF) with each joint actuated by a coreless DC motor via distributed control with controllable compliance. Using a computer vision system on the head, IMU in the torso and multiple force sensors on the foot, DARwIn can implement human-like gaits while navigating obstacles and will be able to traverse uneven terrain while implementing complex behaviors such as playing soccer.

Starting as a feasibility study to investigate the possibility of designing and fabricating a small scale humanoid robot that walks with two legs, the DARwIn series robots have evolved along with the senior design project from concept to a well oiled machine. From the success of the first senior design project creating DARwIn I, which investigated how to create a humanoid robot with human proportions, range of motion, and kinematic configurations, the second senior design project created DARwIn IIa, which built on the name "humanoid" by adding sensors and intelligence to be able to operate autonomously. The second senior design team also created DARwIn IIb, which improved on its predecessor by adding more powerful actuators and modular computing components. Finally, the third senior design team created DARwIn III, which is being designed to take the best of all the designs and incorporate the robot's most advanced motion control yet. From the success of the undergraduate project developing our DARwIn series humanoid robots, the next step is to have the team develop an affordable, low cost version with focus on ease of manufacturing so that the robotics community will be able to use it as an open humanoid robot platform for education and research.

RESEARCHING DYNAMIC GAITS

DARwIn is a research platform used for studying dynamic gaits and walking control algorithms. With a few exceptions (i.e. the Honda ASIMO, the Sony QRIO, and the KAIST HUBO [2–6]), most legged robots today walk using what is called the static stability criterion. The static stability criterion is an approach to prevent the robot from falling down by keeping the center of mass of its body over the support polygon by adjusting the position of its links and pose of its body very slowly to minimize dynamic effects [4]. Thus at any given instant in the walk, the robot could "pause" and not fall over. Static stability walking is generally energy inefficient since the robot must constantly adjust its pose in such a way to keep the center mass of the robot over its support polygon, which generally requires large torques at the joint actuators (similar to a human standing still with one foot off the ground and the other supporting leg's knee bent). Humans naturally walk dynamically with the center of mass almost always outside the support polygon. Thus human walking can be considered as a cycle of continuously falling and catching its fall: a cycle of exchanging potential energy and kinetic energy of the system like the motion of a pendulum. We fall forward and catch ourselves with our swinging foot while continuing to walk forward. This falling motion allows for our center of mass to continually move forward, not expending energy to stop the momentum. The lowered potential energy from this forward motion is then increased again by the lifting motion of the supporting leg. One natural question that arises when examining dynamic walking is how to classify the stability of the gait. Dynamic stability is commonly measured using the Zero Moment Point (ZMP), which is a point defined as "the point where the influence of all forces acting on the mechanism can be replaced by one single force" without a moment term [7]. If this point remains in the support polygon, then the robot can apply some force or torque to the ground, which in turn means the robot can have some control over the motion of itself (the system). Once the ZMP moves to the edge of the foot, the robot is unstable and can do nothing to recover without extending the support polygon (planting another foot or arm). Parameterized gaits can be optimized using the ZMP as a stability criterion or stable hyperbolic gaits can be generated by solving the ZMP equation for a path of

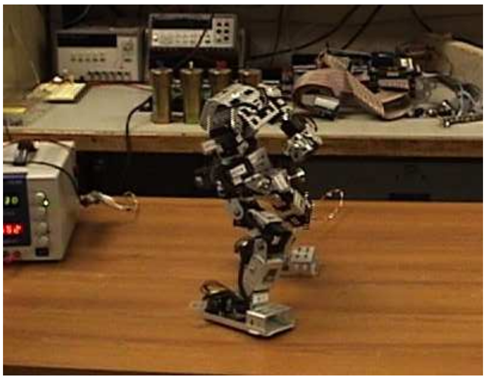

Figure 1. CYCLOID ROBOT FROM ROBOTIS THAT STUDENTS WERE ABLE TO MAKE STAND UP AND WALK.

the center of mass. Additionally, the ZMP can be measured directly or estimated during walking to give the robot feedback to correct and control its walking. DARwIn is developed and being used for research on such dynamic gaits and control strategies for stability [4, 8].

THE SENIOR DESIGN PROJECT

The undergraduate senior design project is a six credit course required at the Virginia Tech Mechanical Engineering Department that lasts for two semesters and builds on all prior education while adding real-life experience. Among the many different senior design projects, this paper will present the Dynamic Anthropomorphic Robot with Intelligence (DARwIn) project; participating are approximately 8-10 seniors, 2-3 additional undergraduates, 2-3 graduate students, and 1-2 faculty. Currently in its third year, the DARwIn project has evolved in organization, management, and educational value along with evolving with DARwIn's design.

Feasibility Study

The first year of the DARwIn project was a feasibility study both for the project and the design of the robot. If the undergraduates were able to design and build a humanoid robot, and get the robot to walk, then the project would have good potential as a senior design project each year. The students were given very little requirements and structure for the project and were expected to organize and manage themselves. This was done to teach the students about working with each other and how to work with management. Using the entire academic year, the undergraduates were able to design and fabricate DARwIn I and make the humanoid walk. While designing DARwIn I, the students were able to make a similar humanoid robot walk that used the same motors (Fig. 1).

The development of DARwIn I focused on the design for

Figure 2. DARWIN I.

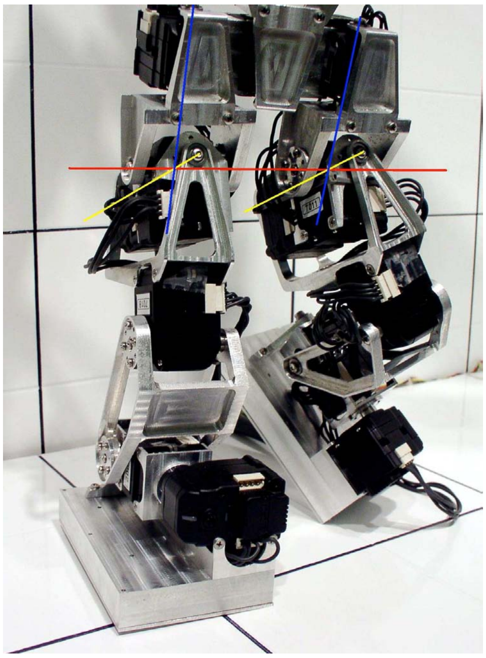

Figure 3. CLOSEUP OF DARWIN'S HIPS SHOWING KINEMATICALLY SPHERICAL JOINTS.

anthropomorphization (Fig. 2). Since the results of testing and experimentation using DARwIn would be compared with actual human data, it was necessary to design the robot to physically mimic a human as closely as possible. Using human proportion data, the undergraduates designed DARwIn I's links to be in proportion to its height and its joints to follow the range of motion of an average male human. Many humanoid robots being developed at research labs today or marketed as hobbyist toys are often made just to "look" like a human. However, the senior design team took great care to design DARwIn I's proportions to be nearly identical to that of a human's. Not only is DARwIn I scaled in dimensions similarly, its primary joints are kinematically equivalent to those of humans'. Humans have a ball and socket joint at the shoulders and hips, allowing three axes of rotation about a single point (Fig. 3). Though DARwIn does not have a ball and socket joint, it achieves the identical kinematics with three motors' axes of rotation intersecting at a single point– making it equivalent to a ball and socket joint. Not only does this make the kinematic configuration closer to a human's, it also simplifies the mathematics involved in controlling and creating the motion of the robot.

DARwIn I has 21 degrees of freedom (6 in each leg, 4 in each arm, one in the waist), 4 force sensors on each feet, a 3 axis rate gyro, a 3 axis accelerometer, and space to house a computer and batteries for powering the motors, sensors, and computing equipment. DARwIn I's links are fabricated out of bent sheet aluminum. The robot uses Robotis' Dynamixel DX-117 motors for the joints and Flexiforce force sensors in the feet. The motors operate on a serial RS485 network, allowing the motors to be daisy chained together. Each motor has its own built-in potentiometer and position feedback controller, creating distributed control [9]. With very little guidance, the senior design team was able to design a very sophisticated humanoid robot, taking into consideration kinematics, proportions, sensors, motors, etc. While doing so, the undergraduates organized their own management for the team. They broke the project down into subteams with hardware, electrical, and software teams. In addition to the sub-team meetings, the group meetings were organized by appointing a group leader and a bookkeeper to make the meetings more efficient and beneficial. In addition to learning about mechanical design, mechatronics, and programming, the undergraduate senior design team learned about team management and project organization.

Second year

A student from the first undergraduate senior design team that created DARwIn I continued on as a graduate student in the Robotics and Mechanisms Laboratory studying Zero Moment Point (ZMP) stability for humanoid robots. In addition to research, the graduate student helped to lead the new senior design team in building the next generation of DARwIn robots. Using DARwIn as a platform for testing and researching, the graduate student had a vested interest in the senior design team's suc-

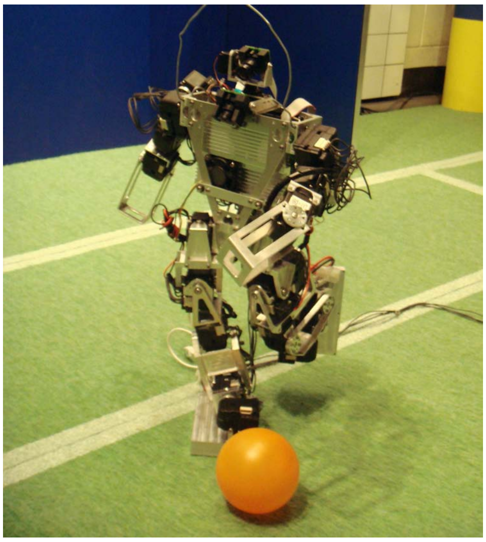

Figure 4. DARWIN IIA.

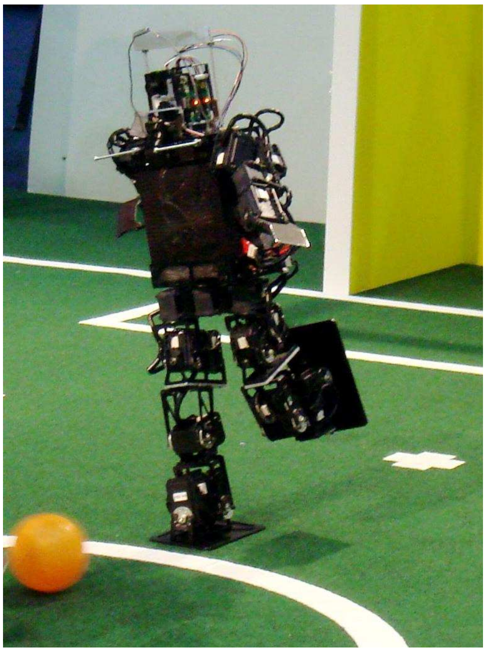

Figure 5. DARWIN IIB.

cess. Additionally, using the experiences from the previous year, the graduate student was able to accelerate the undergraduates' design process and put an organizational/management structure in place at the beginning of the year. The accelerated pace allowed the senior design team to double their progress, creating two robots: DARwIn IIa and DARwIn IIb. Not only did the team create two robots, but also added onboard computing and sensing. The second year of the senior design team created DARwIn IIa (Fig. 4), which builds on its predecessors with improved mechanical design, more sensors, and added intelligence. Control of the robot's motion for stability, especially for bipedal walking, often requires precise knowledge of link locations and movement. By making the robot's links as stiff as possible, there is less error in the system. If a link in ankle were to flex just 1 or 2 degrees, the upper body would sway as much as 30 millimeters. Analyzing the design of the links using finite element analysis and using a CNC machine to mill out the links from solid blocks of aluminum, the stiffness of DARwIn's links were maximized and weight minimized.

DARwIn IIb is based on the design of DARwIn IIa, but with improvements in all categories (Fig. 5). The motors used for articulating DARwIn's joints were replaced with a motor with twice the torque. DARwIn's link design was further refined to create even lighter weight parts. The entire computer, sensors, electronics package, and computer ports were mounted to a custom designed heat sink as a single module. This module is attached to the robot body using shock mounts, which allows easy access and removal while protecting the equipment from shock when falling.

DARwIn II a/b's Electronics Architecture Overview

In addition to its improved mechanical design, DARwIn II a/b also has added intelligence to meet the research demands and to allow it to perform higher level tasks, like playing autonomous soccer. DARwIn II a/b's electronics provide power management, a computing architecture, and a sensing scheme aimed at providing information on salient environmental features. DARwIn's power is provided by two 8.2V (nominal) lithium polymer batteries, usually attached to the lower body (legs or feet) to keep the robot's center of gravity below its waist. These batteries provide 2.1 Ah, which gives DARwIn a little over 15 minutes of run time. The power circuit provides 3.3V, 5V, and 12V for the various digital electronics within DARwIn. However, the joint actuators, Robotis Dynamixel motors, are run directly off battery power, which drops from 16.4V to 14.8V during runtime. In addition to providing power to DARwIn's main systems, the power electronics allow for an external power connection and a seamless switch between power sources. Additionally, this circuit prevents reverse polarity, overvoltage, over-current, and under-voltage conditions from damaging the computing, sensing, and actuation components. DARwIn's computing architecture is setup to use a centralized control scheme, which is run on a PC104+ computer with a 1.4GHz Pentium M processor, 1 GB of RAM, compact flash drive for storage, IEEE 1394 card, serial communication, USB, Ethernet, and IEEE802.11 for wireless communication. The operating system is LabVIEW Real-Time [10]. DARwIn also has two IEEE 1394 (Firewire) cameras and a 6 axis rate gyro/accelerometer (IMU) for vision and localization. The cameras capture 15 frames per second at 640 x 480 resolution and 30 frames per second at 320 x 240 resolution RGB. The cameras are attached to a pan and tilt unit, which allows the robot to better look at its surroundings. Two lithium polymer batteries in the feet allow the robot to be powered autonomously.

DARwIn II's Software Architecture

For high level behaviors, such as playing autonomous soccer, both versions of DARwIn II use a similar software architecture, which utilizes a behavior-based control scheme [11]. Reactive based control has the distinct advantage of being simple and robust. Figure 6 shows the simplified software flow diagram used for RoboCup 2007. Raw sensor data is processed into meaningful information, which gives the robot ball position, goal position, opponent positions, and orientation [12]. This information is used by the individual behaviors to dictate their respective actions. The necessary behaviors for any given situation are determined using a Hierarchical State Machine. If in any given situation, two competing behaviors are chosen, then the integrator is used for arbitration. The motion control module receives higher level walking commands, head motion commands, and special action kicking or diving commands. The motion generator creates the necessary motion to perform these commands while using orientation information to correct and stabilize the bipedal walking gait. For inter-process communication, DARwIn's software components comply with the SAE AS-4 JAUS (Joint Architecture for Unmanned Systems) protocol. The individual modules of Perception, Behavior Control, Motion Control, and Game Control are now implemented as JAUS components with all interactions between modules occurring via JAUS messages. This peer-to-peer, modular, implementation for interprocess communications allows for automated dynamic configuration and the ability for each software component to run on any computing node on the network. Standardized message routing and data serving also promotes reusability of code for future robotics projects and DARwIn III is the first ever humanoid robot to be considered JAUS inter-operable.

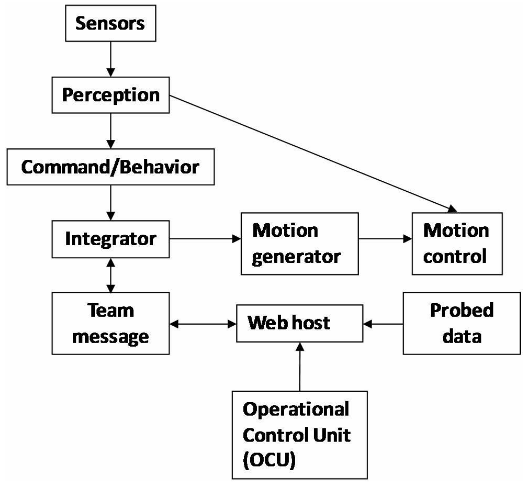

Figure 6. FLOW DIAGRAM OF SOFTWARE USED IN DARWIN.

REFINED RESEARCH AND DESIGN

Currently in its third year, the undergraduate design team is still coming up with innovative designs for DARwIn. Much of this innovation is fostered by an excellent management structure that was adopted from a commercial product development project manager. Overall, the process takes more paper work and bureaucracy, but it improves efficiency by ensuring proper design, thought, and consideration up front. After a couple weeks of bringing the undergraduates up to speed on the current status of the project, the undergraduates, graduates, and faculty come up with a list of items the project should produce. Each of the seniors creates a "Specification" that details each what the problem is for each item, its solution, its alternative solutions, and how the item impacts other people on the team. By writing a "Specification", the students learn more about the problem they are solving and have a better idea of how to solve it before they begin design work. The group is still divided into the same sub-teams-each with a leader. The overall undergraduate group also elects an overall leader. In addition to the undergraduates' organizational structure, the graduates have also naturally organized. Now with three graduate students, there is an overall project leader and then "experts in their field," who handle items pertaining to the project that may be too complex for the undergraduates or pertain to the graduate's research; the fields being software architecture, electronics architecture, and walking behaviors. Overall, the tiered organization divides work fairly among the undergraduates and graduate students working on the project. With the help of a new organizational structure, the project looks to further improve on the successful designs of the previous versions with DARwIn III. Improvements are being made in computing power, software architecture, vision routines, walking gaits, stability control, and mechanical design. Faster loop times and more complex walking gaits along with a more robust vision system require additional processing power, which has led to the addition of a microcontroller in DARwIn III's design. The microcontroller controls gait generation and stabilization, leaving the PC104+ computer to run the behavior and vision routines. The PC104+ board and the microcontroller communicate with one another over an RS232 network, with the microcontroller communicating over an RS485 network with the Robotis Dynamixel motors. The current PC104+ 1.4 GHz board will be replaced with a Core 2 Duo PC104+ board running at approximately 2 GHz. The new board will provide enough processing power to run the new vision, behavior, and walking gate algorithms. The senior design team is also investigating other software architectures such as Microsoft Robotics Studio. The final implementation of DARwIn's electronics package calls for a large reduction in weight, power consumption, and size, while increasing performance. To this end the PC104+ Core 2 Duo will be exchanged with our old PC104+ 1.4 GHz Pentium M and an FPGA added for each system such as behavior and vision. Switching to our original computer provides a lower power computing platform and still enables DARwIn to easily interface with existing computer technology as well as run higher level code and GUIs that an end user may need. The FPGAs will provide the needed performance boost by allowing multiple systems such as walking, vision, and behaviors to be more complex and run simultaneously on their own processors without impinging on each other's operation. More importantly, DARwIn's reaction time to an ever changing environment will decrease as a result of the parallel architecture. In addition, the specific I/O required by each system will be on the FPGAs-eliminating the need to add I/O boards, which is the reason for DARwIn III's larger computing package. The walking algorithms running on a microcontroller could be instantiated on an FPGA and control custom joint actuators instead of the Robotis Dynamixel motors. The decision to use alternate joint actuators is motivated by the fact that currently the controller within the motors is company intellectual property, and the ability to design the motors' controller is becoming a necessity. Finally, all systems will be connected to deterministic buses so that the delay caused by information transfer is known. The current setup in DARwIn III does not use feedback from the Dynamixel motors because the proprietary code shares information in a delayed fashion on a non-deterministic, polling architecture bus. By using our own joint actuators, many of these problems can be subverted and a deterministic bus such as EtherCAT can be implemented. Without such a bus, large latencies and indeterminism will make it very difficult to implement active real-time controllers. DARwIn III will use a world model to dictate its behavior. A world model is a completely known virtual model of the environment with the states of the model updated from sensor inputs. A world model allows for planning, which reactive behavior does not, and leads to more efficient behaviors.

COMPETITIONS

In addition to serving as research platform, DARwIn also served as the first and only US humanoid entry to qualify for the international autonomous soccer competition, RoboCup 2007 [13]. RoboCup is a soccer competition between autonomous robots. The program's goal is by 2050 to have fostered a team of humanoid robots capable of defeating the human World Cup champions in soccer. Started in 1997, RoboCup did not introduce the humanoid league until 2001. The humanoid competition requires that the robots be fully autonomous-all computing, sensing, and power must be onboard the robot. RoboCup is a challenging and exciting arena for humanoid robotics. RoboCup brought a lot of attention and excitement to the senior design project. The idea of going to competition served as a motivator in getting the students to work harder. The competition also served as a benchmark to compare DARwIn against. Using ideas from other robot designs and software, DARwIn's design continues to improve. Being the only US team in the humanoid division brought a lot of attention to DARwIn, resulting in a lot of publicity and press, which is good for fund raising [11, 14–18]. DARwIn won many other awards including:NI Week Best Application of Virtual Instrumentation overall (2007), AAAI Technical Innovation award (2007), and 2nd Place in the ASME international Student Mechanism Design Competition (2006).

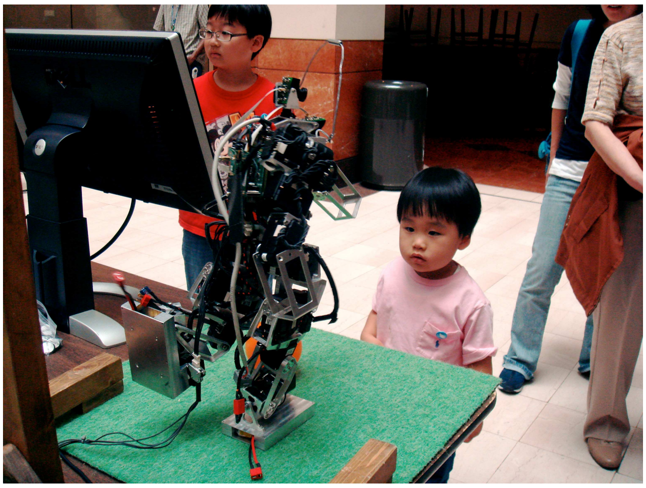

Figure 7. PUBLIC DEMONSTRATION AT NSF HEADQUARTERS IN WASHINGTON DC TO EDUCATE AND EXCITE CHILDREN ABOUT ROBOTICS.

Public demonstrations of the soccer playing robot educated the community and brought excitement to the field of robotics (Fig. 7).

CONCLUSIONS, OBSERVATIONS, AND LESSONS LEARNED

Combining graduate research with an undergraduate senior design project on humanoid robotics seemed to work well to produce a sophisticated humanoid robot research platform and to foster a good research environment. Having the graduate student's research partially depend on the success of the senior design project gives the graduate an obvious motivation to help the seniors as much as possible to ensure their success. The graduate student also benefits greatly by saving time on designing and fabricating a sophisticated research platform. Having an international competition for the project-especially one that is internationally popular-helps to motivate the undergraduate students and also brings public attention and media, which can lead to additional funding for the project. An organizational structure is extremely desirable to have in place to make the design process efficient. Having an experienced member (either faculty or graduate student) heavily involved in the project also seems to be very important in achieving excellent results in design. The international competition is a fantastic motivator, but too much stress on the competition tends to distract the team from the real goal of the project, which is to create a research platform. Too much stress on competition can also be very disappointing if the competition results are not as expected. In any case, the competitions give valuable experience and design ideas, which can be used for future projects.

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