

# Ideas and Technology of Control Systems

*NSF Workshop for Middle School and High School Students and Teachers*

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**Figure 1:**

Students attending the NSF Workshop for Middle School and High School Students and Teachers held at the CDC 2003, Maui, Hawaii. Around 250 students from the Maui School District attended an all-day workshop on control systems.

**Figure 2:**

From left to right: 2003 IEEE CSS Vice President for Technical Activities Miroslav Krstic, 2003 IEEE CSS President Cheryl Schrader, IEEE CSS Technical Committee on Control Education and CDC 2003 Education Activities Chair Bozenna Pasik-Duncan, and NSF Program Director Kishan Baheti. Dignitaries from the IEEE Control Systems Society, the 2003 IEEE CDC, and the USA National Science Foundation welcomed the student participants.

**Figure 3:**

Representation of how a driver uses feedback to follow other cars at a safe distance. Our eyes sense the distance between our car and the one ahead, our brain determines whether we must speed up or slow down to match the desired distance, and our foot actuates the car speed so that we drive at the desired distance.

**Figure 4:**

Computer Intelligent Model CAR (CIMCAR) with servo motor and batteries. This model car has a servo motor and batteries. CIMCAR's speed is controlled by the current to the motor. Using a sonar sensor for its "eye" and a microprocessor for its "brain," the CIMCAR can be controlled so that it stops before hitting a wall, even if it is going up or down a ramp.

**Figure 5 (a):**

(Uncontrolled system.)

**Figure 5 (b):**

(Controlled system.)

**Figure 5 (c):**

(Automatically controlled system.)

**Figure 5:**

Block diagram representation of the progression from (a) an uncontrolled system to (b) a controlled system to (c) an automatically controlled system. Notice that in the controlled system, the operator takes some control action to obtain the desired behavior. In the automatically controlled system, the control action is determined based on both the desired and actual behavior.

**Figure 6 (a):**

(Water tank system without automatic controller.)

**Figure 6 (b):**

(Desired behavior graph.)

**Figure 6 (c):**

(Water tank system with automatic controller.)

**Figure 6:**

Water tank system (a) without automatic controller, (b) desired behavior graph, and (c) with automatic controller. The water tank has a maximum height, and water enters through a pipe into the top of the tank. The position of a valve in the pipe can be adjusted to control the flow of the water into the tank. The graph shows how the height of the water in the tank varies as a function of time with the proposed controllers. The automatically-controlled system uses a float to automatically cut off the water flow into the tank when the tank is full. This mechanism can be found in flush toilets.

**Figure 7:**

Deadlock in a simple manufacturing system. A defective part must be returned to the input buffer of the machine tool for rework. However, if the input buffer can hold only one part and if there is already a part waiting, then there is a “deadlock” while each part waits for the other one to move.

**Figure 8:**

Close-up of one of the robots that won the championship in Padova, Italy, in 2003. This photo shows the golf-size soccer ball used in the RoboCup soccer competitions. This small-scale soccer game is played according to standard soccer rules by robots designed by teams of students. The robots must operate entirely autonomously during the competition with no intervention or remote control by their human designers.

**Figure 9:**

RoboCup competition with soccer game field. The robots work together in both defensive and offensive plays against the opposing team. Each robot has its own controller. A vision system is required to track the locations and actions of all robots and the ball on the playing field. A centralized controller uses this information to send play information to the individual robots so that they can work together against the opposing team.

**Figure 10:**

Interior of autonomous vehicle designed for competition in the DARPA Grand Challenge race. Actuators are installed in the driver's seat area to automate the mechanical actions that a human driver would make.

**Figure 11 (a):**

(Stabilization of triple inverted pendulum.)

**Figure 11 (b):**

(Single inverted pendulum being passed between two robots.)

**Figure 11:**

(a) Stabilization of triple inverted pendulum and (b) a single inverted pendulum being passed between two robots. These mechanisms were stabilized using a vision system to sense the pendulum angles.

**[Outrigger Sidebar] Figure 1:**

Modern outrigger canoe riding a wave, with the outrigger shown in the foreground. This ancient technology is still widely used.

**[Outrigger Sidebar] Figure 2:**

Drawings of a Hawaiian style single outrigger canoe. On the left is a typical view of the canoe. On the right is a cross section showing how the outrigger improves the righting moment of the canoe. The single outrigger design is far easier to manufacture than a double hull canoe, which requires matching tree trunks.

The IEEE Control Systems Society's Technical Committee on Control Education strives to bring control system concepts and technologies to the awareness of high school and middle school students and teachers. Control is used in many common devices and systems, such as computer hard drives, VCRs, automobiles, and aircraft, but is usually hidden from view. The goal of this Committee is to promote an increased awareness among students and teachers of the importance and cross-disciplinary nature of control and systems technology.

To help meet these objectives, a workshop was held at the 42nd IEEE Conference on Decision and Control (CDC 2003) in Maui, Hawaii, on Tuesday, December 9th, 2003. About 250 students from the Maui School District, which spans the islands of Maui, Lanai, and Molokai, attended this workshop, escorted by their teachers. In addition, teachers who had attended earlier workshops came from as far away as Florida to participate. Because of space limitations, several hundred additional students had to be turned away from this extraordinary field trip.

Bozenna Pasik-Duncan, Chair of the Technical Committee on Control Education and CDC 2003's Chair for Control Education Activities, organized the workshop with sponsorship from CDC 2003 and funding from the National Science Foundation (NSF) and the University of Kansas. Dr. Kishan Baheti, Program Director in NSF's Division of Electrical and Communications Systems, provided the NSF funding. The Technical Committee on Control Education has organized similar workshops at a number of earlier conferences. Workshops for high school teachers were held at the American Control Conferences in Chicago (2000) and Denver (2003). A workshop for high school students was held at the 41st IEEE Conference on Decision and Control in Las Vegas, Nevada, in December 2002.

Control system experts from our technical community were recruited to present at the workshop based on their willingness and ability to present control topics at an appropriate level for secondary school students. These experts sought to describe control and system technology ideas to the students and teachers and to expose them to control applications and research. Workshop presenters included Raffaello D'Andrea of Cornell University, Chris-

tos Cassandras of Boston University, Theodore Djaferis of the University of Massachusetts, Richard Murray of the California Institute of Technology, Mark Spong of the University of Illinois, and Katsuhisa Furuta of the Tokyo Denki University. In addition, Brian Rosen of Pixar Animation Studios, Kishan Baheti of the National Science Foundation, Shane Haas of AlphaSimplex Group, and Suzanne Lenhart of the University of Tennessee presented related dynamic system, nanoscale system, and probability topics.

The workshop began with welcomes from dignitaries from the National Science Foundation, the Control Systems Society and CDC 2003. These included Vasundara Varadan, NSF Division Director for Electrical and Communications Systems, Control Systems Society President Cheryl Schrader, and CDC 2003 General Chair Frank Lewis, among others. Technical Committee Chair Bozenna Pasik-Duncan opened the workshop.

During the course of the day, the students and teachers learned about the power of feedback, the joys and perils of automation, robots playing soccer, and an autonomous vehicle race. They also heard about how animation and lighting of characters is done for movies, the control of inverted pendula, embedded systems, careers in mechatronics, the new field of nanotechnology, and the importance of information in the financial markets. The students played a game, developed for the high school level, that demonstrates the non-transitivity of probabilistic phenomena.

The National Science Foundation offers support to those researchers who want to involve K-12 teachers in their funded research or to assist in the development of suitable materials for K-12 classrooms. Kishan shared information about the NSF Research Experiences for Teachers program with the audience, which support the involvement of a teacher in funded research. The Technical Committee on Control Education also plans to assist in the development of appropriate materials so that students who are unable to attend a workshop such as this one can still be exposed to these topics. With the appropriate lesson materials, and the appropriate exposure themselves, teachers will be able to bring these topics into their regular classes.

# The Power of Feedback

Ted Djaferis gave several examples illustrating the use of feedback, including walking, the outrigger canoe, body temperature regulation, and collision avoidance in automobiles.

When walking, we use our eyes to sense our position and observe our environment. We continuously monitor our position and compare it to our desired trajectory. We adjust our steps to move closer to our desired trajectory and avoid obstacles in our way. Taking our current sensed position and using this information to plan our future steps is referred to as a feedback strategy. Consider how difficult it is for blind people to walk because of the absence of feedback. A walking stick is used to partially replace feedback capabilities.

The temperature in the human body is regulated naturally. Whether we are in the sun or in an air-conditioned room, our body temperature stays close to our normal body temperature. This normal temperature may vary from one person to another or from one time in our biological cycle to another, but it varies relatively little in response to changes in our external environment.

An example of feedback that is local to Hawaii is the outrigger canoe. The outrigger canoe made possible travel across the Pacific Ocean in ancient times. Ted previewed this example and announced that Danny Abramovitch would discuss this topic in a plenary talk the next day. (See the Outrigger sidebar for more information.)

When we drive, we avoid collisions by driving at a safe distance from other cars. To achieve this goal we must monitor the distance and modify our actions depending on what we sense. If we wish to drive 30 feet behind another vehicle, then we must look to see if we are closer or farther than that distance and adjust our position accordingly. A functional diagram of how this adjustment is accomplished by the typical driver is shown in Figure 2. Luxury cars such as Mercedes or Lexus models have systems that automate this process by employing a vehicle radar system that either warns the driver or applies partial braking.

Ted shared a photo and video of CIMCAR (Computer Intelligent Model CAR), a small model car operated by a servo motor, powered by batteries, with its speed controlled by the current to the motor. Without feedback, the car can be made to stop at the right place before a wall if it is on a level surface by turning on and off the motor at the appropriate pre-computed times. However, if the car is then placed on a ramp sloping down and uses the same pre-computed on-off times, it slams into the wall. If the distance between the car and the wall is measured (by a sonar sensor) and that information is used to determine how to control the motor (feedback), the car again can be made to stop at the desired distance away from the wall. Sensors, actuators, and micro-controllers are used to implement the control strategy. The algorithms are first tested using computer simulation before experiments are conducted on the CIMCAR.

Control engineers solve automatic control problems in service to humanity using science, mathematics, and engineering principles and practices, along with software and hardware. They apply their work to a diverse set of systems that may have electrical, mechanical, chemical, hydraulic, financial, or biological characteristics. Automatic control is a fascinating field of study. It is universal, multidisciplinary, helps one develop a systems viewpoint in the solution of problems and allows one to work in theory, develop software, and build hardware.



# Joys and Perils of Automation

Christos Cassandras of Boston University spoke about automating the control of both physical and man-made systems. He provided some basic definitions for the middle school and high school audience, the essence of which are

- System: A group of objects working together toward a common purpose.
- Control: To exercise restraining or directing influence over; to regulate the system.
- Automation: An automatically controlled operation of a system to make the right decisions.

Christos showed block diagrams to illustrate the progression from uncontrolled system (Figure 5 (a)), to controlled system (Figure 5 (b)), to automatically controlled system (Figure 5 (c)). For example, suppose a tank of water with fixed height  $K$  is being filled from a pipe at the top with the pipe's flow rate controlled by a valve, with maximum flow rate of  $\rho$ . At time  $t$ , the tank is filled to height  $x(t)$ , which must be kept less than  $K$ . The valve allows water to flow into the tank at rate  $u(t)$ , where  $0 \leq u(t) \leq \rho$ . If the tank is initially empty, how do we fill it completely without overflowing by controlling  $u(t)$ ? This control objective is the “desired behavior.” (Figure 6 (a))

One control solution is to select the flow rate  $u(t) = \rho$  until  $t = K/\rho$  and  $u(t) = 0$  after  $t = K/\rho$  (Figure 6 (b)). What could go wrong? This solution works only if  $K$  and  $\rho$  are known precisely. In addition, the solution requires an accurate clock in the controller. Furthermore, suppose there were a leak in the tank or someone added water to the tank? This controller does not modify its operation if there are disturbances in the system, and the result in those cases would be an incorrect behavior.

Instead, we use feedback control to automatically control the tank until it is full. The controller forces the flow  $u(t) = \rho$  while  $x(t) < K$ , but  $u(t) = 0$  when  $x(t) = K$  can be

implemented by using a float connected to the valve. It is now becoming clear that we are modeling a flush toilet! The float blocks the input of water automatically when the tank becomes full (Figure 6 (c)). This mechanism, which is the basis for how toilets work, is so effective it has remained unchanged for generations!

although automation has a cost, namely, the price of the float and related parts, it saves us from poor system performance when there is variability or disturbances. The resulting control  $u(t)$  and the state  $x(t)$  are the same as when the open-loop control is used, for the case when there are no disturbances on the system.

Our refined definition of automation is “putting together control and feedback.” With this definition, some other examples of automation include the use of TCP/IP for Internet congestion control, autopilots in airplanes, and the control of train speed when approaching a station platform.

We can design controllers for physical systems or for human-made systems. Physical systems, for example the toilet, must satisfy natural laws, such as the conservation of mass. The values of the state of a physical system are generally real numbers and such systems are often time-driven. In contrast, human-made systems can be created with any rules that the designer selects. This choice can result in a real mess! An example of a human-made system is an ATM machine with a line of people waiting for service. In this system, the state, that is, the number of people waiting in the line, takes only integer values. Events, such as the arrival of a new person in the line or the push of a button, can change the state. Control protocols may take the form of the fair-play rule first-come-first-served. Such control rules, although fair to people, may conflict with priorities for maintenance or medical help, as in a hospital.

When we look for control solutions for these man-made systems, we find that computers can be rather dumb. Consider the example of a machine tool that operates on widgets. Suppose there is a buffer in front of a machine that can hold only a single part, and suppose the machine tool can only hold a single part. The machine will operate on the part and

then either pass it on to an output area if the operation is successful or return it to the input buffer if it is defective. Unfortunately, if there is a waiting part in the input buffer, the machine tool will be stuck holding the defective part. Part 1 in the machine waits for the input buffer to be free, while part 2 in the buffer waits for machine to be free (Figure 7). This problem is called *deadlock*.

Here is a common *live-lock* example involving people. Suppose that two people are approaching each other in a hallway. Both people both decide to move out of the way by stepping toward the side of the hallway. Unfortunately, they both step toward the same side, still blocking one another. Next, they both move toward the other side, still blocking each other. Have you had that happen to you? The same problem arises in computer buses when two computers try to talk on the bus at the same time. The computers must try to talk again at random times or else there will be live-lock.

Similar man-made systems, where appropriate analysis and scientific expertise are needed for design and problem solving, include communication networks, manufacturing systems, traffic systems, and elevators, software systems, and video games. To illustrate such a system, Christos showed the students photos of a computer-controlled LEGO car factory that he uses in his courses. In real-world applications, computer simulations are used to analyze and validate solutions that are designed before they are implemented on a real system.

# Robots Playing Soccer

Raffaello D'Andrea described how university students under his supervision design and build small robots and the control and communication systems to support their operation. The robots play a scaled-down version of soccer, using balls about the size of golf balls (Figure 8). The game is played according to regular soccer rules; for example, holding is not allowed. The robots must play autonomously with no human involvement once the game begins. Student-designed robotic soccer teams compete in national and international tournaments, leading up to the RoboCup world championships.

The control structure here is more complex than those described above. Hierarchical control is used, separating local control tasks for robot operation from the centralized planning required for the robot team's play strategies. A vision system is implemented so that the information is available not only on your team's robots' locations, but also on the location and behavior of the other team's robots and the ball. A communication system is needed to pass information between the vision system, the centralized controller, and the localized robot controllers. Physical design decisions include robot size, acceleration, speed, maneuverability, and inertial navigation. Low latency (meaning short time delay) is critical to the network design.

Other considerations include the following. For the local robot controller design, the robot-motor system dynamics has to be understood. Motion planning for a single robot includes path planning for obstacle avoidance ensuring that the robot is where it is needed when it is needed there. High level "plays" include both offensive and defensive strategies, and transitions between them as appropriate. The time required for a play must be kept small in certain situations, otherwise, the energy used has to be minimized. This objective determines the choice of control actions and trajectories selected. Algorithms are thoroughly tested using simulated games before they are implemented.

Raff showed video fragments of the international competitions in which the Cornell Autonomous Robotic Soccer Team participated (Figure 9). The Cornell team has won four

championships in the last five years. Competition highlight videos are available on Raff's web site ([www.mae.cornell.edu/raff](http://www.mae.cornell.edu/raff)).

# Autonomous Vehicles: Racing from Los Angeles to Las Vegas

Richard Murray of the California Institute of Technology gave an exciting talk about autonomous vehicles. The autonomous vehicles in this case are 4-wheel-drive vehicles that must race across the desert from Barstow to Las Vegas. The vehicles are not allowed to have a driver or any kind of remote control. The fastest truck that completes the route in 10 hours or less will win the grand prize of \$1 million, a detail that caught the students' attention. The race will be held on 3/13/04.

Two hours before the race participants will be given a set of 1000 GPS way points and a corridor 10 meters wide to 10 km wide to stay within. The truck has no information about a feasible route within the corridor. The vehicle is not permitted to run into any other vehicles, Joshua trees, which are protected plants, fences, or other obstacles. The race is a 250 mile run with dirt roads, trails, rough roads, open desert, lake beds, overpasses to go under, water crossings, and dead ends.

For a professional desert racer with prior experience on a familiar course, the trip would take about 4 hours. On an unfamiliar route, however, it would take the same driver 8 hours. It is clearly a serious challenge to have an autonomous vehicle navigate the course in less than 10 hours.

Richard showed pictures of some of the vehicles that are being prepared for the race. For the CalTech vehicle, the sensors consist of 12 cameras for vision, GPS navigation system, inertial sensors (accelerometers and gyros), LADAR (laser radar scanning), and other devices. For actuation the driver's seat has been entirely replaced with automated parts. A total of 10 on-board computers are used for computation.

A video of a human-driven trial run with the truck hurdling through the desert showed the difficulty of keeping to an ill-defined path. The students were fascinated by the difficulties of the task. For example, one poignant question that was asked was: "If the truck

kills someone, are you liable for murder?" Richard assured the students that this event could not occur.

# Better Movies through Mathematics

Brian Rosen described how animated movies are made and the important role of mathematics. His first point, illustrated with cartoon characters that were immediately recognized by the students (but not all of the CDC attendees!) was that art comes first, that is, you draw characters first. Next comes the mathematical representation of how to view or visualize the art. Much of the basic mathematics of visualization can be described at a level that can be understood by high school students.

Most basic is the question of how to represent a line, which is parameterized in terms of a start point  $(x_0, y_0)$  and an end point  $(x_1, y_1)$  with  $t$  as the line parameter with  $0 \leq t \leq 1$ . He gave several steps first, then finally gave the parametric form of the line  $(X, Y) = (X(t), Y(t))$  in both coordinates:

$$X(t) = x_1t + x_0(1 - t),$$

$$Y(t) = y_1t + y_0(1 - t).$$

Representing various curves is in terms of third degree polynomials with general coefficients  $\{c_0, c_1, c_2, c_3\}$  so that

$$X(t) = c_1t + c_0$$

is a straight line needing 2 points to describe it,

$$X(t) = c_2t^2 + c_1t + c_0$$

is a parabola needing 3 points to describe it, and

$$X(t) = c_3t^3 + c_2t^2 + c_1t + c_0$$

is a cubic or third degree polynomial needing four points to describe it. Beyond the straight line, knowing the start and end is not sufficient to determine the constants  $c_i$  for  $i = 0, 1, 2, 3$ , and some other information such as a slope is needed. However, using a little bit of high school calculus, we can also write the slope with respect to the parameter  $t$  for the cubic as

$$X'(t) = 3c_3t^2 + 2c_2t + c_1.$$



Now we use splines of curves to glue together pieces described by cubic polynomials since splines rely on both point and derivative information to give smooth transitions between spline pieces.

If we go to three dimensions, then we need three cubic polynomials, one for each dimension, and then get surfaces of a figure of interest represented by meshes, which are sets of neighboring points on the surface of the figure. We move the underlying surface mesh to get motion and more realism in animated films and games. We get animation.

The animation team consists of many people organized into departments. At Pixar the number of team members could be as much as one hundred, depending on the film. The art department provides expressions for the characters. Flexible meshes are more detailed on the face to capture expressions. To do this, we need complex controllable meshes that can distort. Human reference subjects are used to mimic how the eyes move, say from video tapes displaying eye movements. The goal is to capture details such as the movement of the skin and muscles when the eye moves.

It is also important in animation to capture the effect of light reflecting off of surfaces. For example, a sphere or ball that is just orange everywhere looks like a circle, unless we model how light interacts with the surface. For ideal surfaces the reflection is specular, that is, the light is reflected directly to the viewer. This interaction for real surfaces when the object is not smooth and has imperfections leads to a dot product. Specifically, diffuse light reflection is proportional to the dot product ( $\cdot$ ) of the normal  $\vec{N}$  to the sphere and the direction  $\vec{L}$  of the source of light given by

$$\text{Diffuse} = \vec{N} \cdot \vec{L}.$$

However, the eye of the viewer also receives directly reflected light such that

$$\text{Brightness} = \text{specular} + \text{diffuse}.$$

Specular color has a shaping effect that is iridescent and modifies specular light. In reflection, color comes from the environment and color shape reflection. Another technique is procedural displacement using sine waves and random noise to provide greater realism.

To obtain realistic lighting effects, there are teams of people who adjust computer light sources. An advantage of the computer-generated lighting is the ability to do things that are not possible in real life, that is, if the scene were being filmed. For example, light shines only on part of the scene in animation but not in real life. Also negative lighting is possible, as well as different colors appearing on different objects in a scene.

Production of an animated movie can take three years, one year for concept development, two years for production and roughly 200 people during production.

One student asked: How long does it take to learn the necessary math? Brian replied that he learned computer graphics in his sophomore year of college. Three years later he had a job in animation, in which he continued to learn on the job.

This talk was a resounding success with cheers from the students. Later, in the panel discussion, Brian answered more questions and gave extended explanations of the role of mathematics including the important role that algebra, trigonometry, geometry, and other areas play in scientific visualization and animation. There were a lot of specific questions on the making of certain animated films and the possibility of sequels to existing films. The subject of computer games also arose, and it was clear that computer games can serve as a motivation for exploring mathematics and computer science. It is clear that this talk made a convincing argument for the necessity of learning mathematics well enough to be able to apply it to science and engineering as well as diverse applications.

Finally, some of these questions led to more general questions in the later session about careers and college, such as the cost of college, the relative benefits of public versus private colleges, what college is like, and how one chooses a major in college.

# Understanding and Controlling the Pendulum

Katsuhisa Furuta showed the students how pendulums could be controlled to stand upright, using videos and equations. In fact, many of the principles of control can be understood by studying the pendulum.

Long ago, Galileo Galilei investigated the periodic swinging motion of a hanging pendulum. Today, a technological challenge is to build a device to keep the pendulum inverted, much like holding an umbrella upward with only a very small grip on the handle. The problem is to exert appropriate control to counter-balance the downward pull of gravity. Video examples were shown of a single pendulum balanced by means of a robot arm using a vision system.

An inverted single pendulum is now a standard demonstration at conferences and in classroom laboratories. However, a composite of two pendulums seems much more difficult, but by using very fast vibrations the inverted double pendulum can be stabilized. Multiple single pendulums mounted on the same platform can be stabilized by fast vibrations of the platform.

The single pendulum, hanging or inverted satisfies the equation,

$$J\theta'' = -mgl \sin(\theta),$$

where  $m$  is the pendulum mass,  $l$  is the pendulum length,  $g$  is the acceleration of gravity,  $J = ml^2$ ,  $\theta$  is the angle measured from the downward vertical axis, and  $\theta''$  is the second time derivative or angular acceleration. For the inverted pendulum, we let  $\theta = \pi - \psi$ , so  $\psi = 0$  corresponds to the marginally stable inverted pendulum pointing upward. Hence, for the inverted pendulum it is easier to use the equation, using a little bit of trigonometry,

$$J\psi'' = mgl \sin(\psi).$$

To have the pendulum swing upward, we can use control to artificially apply gravity in the reverse direction. To accomplish this reversal, we consider the equation

$$J\psi'' = -mgl \sin(\psi),$$

where reversed gravity is modeled by the minus sign on the right hand side of the equation. How can we accomplish this artificial gravity reversal? Although we cannot change the gravitational force of the earth, we can apply an external force to the pendulum that emulates reverse gravity.

Adding a control term to the pendulum leads to the equations become to

$$J\psi'' = mgl \sin(\psi) - uml \cos(\psi),$$

where  $u$  is the control variable. The control (meaning the equation for  $u$  in terms of  $\psi$ ) that makes the right-hand-side of the equation take the form of the pendulum with gravity upwards rather than downwards is

$$u = u(t) = 2g \sin(\psi) / \cos(\psi).$$

Using this controller, we have added a force that makes the pendulum behave as if gravity were reversed.

More videos showed the double-link pendulum being stabilized after the double pendulum is swung up. Even more extraordinary, the triple pendulum was shown stabilized (Figure 11 (a)). Finally, Katsuhisa showed “cooperative control”, the hand-off of an inverted pendulum between one robot and another (Figure 11 (b)). The coordination of the robots is the hard part.

Katsuhisa also told the students about the important and dangerous job of clearing land mines in war-ravaged parts of the world and how that job is becoming automated. This application resonated with the students because a nearby Hawaiian island that had been used for U.S. military target practice has recently been cleared of unexploded ordinance. There are 10 million buried mines in Afghanistan alone, and many more in Cambodia, Vietnam, and Laos. The hand clearing of mines needs to be replaced by machines for safety, and Japanese engineers are helping.

# Future Careers in Embedded Systems, Mechatronics, and Control

Mark Spong spoke on embedded systems and mechatronics, the hybrid combination of mechanics and electronics, and problems that exist in the field.

Cell phones have computers in them, so they are called embedded systems. Embedded systems link together different devices emerging from the Information-Technology (IT) revolution. Mechatronics involves the blending of mechanical systems with electronics such as sensors, actuators, computers, software, and intelligence. Examples of mechatronics include automotive systems, adaptive cruise control, conversion of gas engines to hybrid and fuel cell engines, drive-by-wire, and cam-less engines.

In a traditional car, the car turns when the steering wheel is turned. There are various mechanical linkages in this arrangement. The steering wheel is a danger to the driver in an accident. If the steering column and mechanical connections are replaced by sensors, actuators, and embedded microprocessors, then not only is the steering column eliminated, but also a left-hand drive car can easily be converted to a right-hand drive car.

In a traditional engine, a mechanical cam pushes the rods as it turns to open and close the valves. The cam is a certain shape, and that dictates the timing of the valve operation. If motors are used to open and close valves instead, then complete control of timing is possible. Some of the pistons can be stopped at traffic lights, when the extra thrust is not needed.

Robots are the ultimate mechatronic systems by enabling unmanned vehicles, telemedicine, and automated manufacturing. Mark played a video showing a robot, developed by his students, who played air hockey against a human opponent. At the end of the video, the robot lost control after an unusual maneuver, prompting a series of questions.

## How to Turn a Single Dollar into Billions

Shane Haas gave a talk on how the timing of investments could be used to maximize return on investments (if anyone had perfect information!). A surprising number of the students were knowledgeable about finance, and a few owned stock and so had a personal interest in his talk. He described an investment approach where an investor moved his or her entire investment, at regular intervals, to the best instrument for the next period of time. These could alternate between a savings account with a low fixed rate of return, and a volatile investment such as a stock fund. The portfolio instant rate of return is

$$P(t) = \text{maximum}[B(t), S(t)],$$

where  $B(t)$  is the risk-less fixed rate of return and  $S(t)$  is the risky stock fund rate of return.

Shane used monthly closing data for the period from 1926-2003, updating the portfolio each month according to the formula, for U.S. Treasury bills as low-risk investment and the Standard and Poor's 500 stock index as the high-risk investment (simulating a large stock mutual fund). Starting with one dollar in 1926, the final amount was an amazing \$14.3 billion! If one invested their money in S&P 500 stock index, the \$1 would have yielded \$2171 over that time. In a savings account with a low fixed interest rate, the return would have been \$17.

This perfect market timing investment strategy, that is, switching between the better of S&P 500 or Treasury bill returns, is equivalent to buying treasury bills and a call option on the S&P 500. Remarkably, the Black-Scholes formula can price this option to determine the value of this investment strategy. This analogy motivated a question from our student financial experts about investment or transaction fees, and Shane said that according to the Black-Scholes formula, the fees justified for someone with perfect monthly prediction would be 24% of the investment on an annual basis. Of course, this assumes perfect market timing! If perfectly switched between those two on a daily basis, then it would be far more than \$14 billion with perfect timing.

He also suggested a better alternate market timing portfolio,

$$P(t) = \text{maximum}[\text{Intel}(t), \text{Microsoft}(t)],$$

where the  $\text{Intel}(t)$  and  $\text{Microsoft}(t)$  are the daily returns. With daily perfect market timing, one dollar invested on January 5, 1990, would become \$2.6 trillion on December 5, 2003. Shane encouraged students to download historical data from *finance.yahoo.com* and try other stocks.

Of course, we do not recommend that students try timing the market with their own money. No one has perfect timing, and the minimum investment in a hedge fund ranges from \$1 million to \$25 million. Pension funds, wealthy individuals, and endowment funds typically invest in hedge funds.

# Mathematical Games

Suzanne Lenhart of the University of Tennessee and Past President of the Association for Women in Mathematics ended the program with mathematical games. The students played Hex, which is a positional strategy two-player game, and then conducted some probabilistic experiments with number-spinners relating to the well-known rock–paper–scissors game. By playing these games, the students learned about the property of transitivity. For an example of non-transitivity, if spinner P beats spinner R with probability  $5/9$  and spinner R beats spinner S with probability  $5/9$ , it is not true that spinner P would beat spinner S.



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## **SIDEBAR: Outrigger - The Feedback Mechanism That Allowed the Polynesians to Colonize the Pacific**

During a history session at CDC 2003, Danny Abramovitch presented a plenary paper showing that the outrigger on an outrigger canoe (Figure 1) may in fact be the world's oldest feedback mechanism. The Polynesian migration to the Pacific dates back about 3500 years ago and would have been impossible in dugout canoes without outriggers. Thus, the outrigger was one of the technologies that enabled the Polynesians to colonize the Pacific. At its most basic level, an outrigger consists of a float attached by means of one or more booms to the gunwales (top edge) of a boat (Figure 2). While modern outriggers can be made from a variety of sturdy, buoyant materials, the outrigger float has traditionally been a piece of light wood. Qualitatively, the operation of the outrigger is rather simple. When the canoe rotates so as to raise the float from the water, its weight at the end of a boom provides torque to rotate the float back to the surface. When the rotation of the canoe acts to push the float into the water, buoyancy acts to restore the float to the surface of the water. Thus, the outrigger dramatically increases the roll stability of small canoes.

## **SIDEBAR: NSF Research and K-12 Education — A Winning Partnership**

NSF Program Director Kishan Baheti gave an overview of NSF's mission to support fundamental research and education in science and engineering. Dr. Baheti highlighted NSF's role in the emerging field of nanotechnology that will lead to unprecedented understanding and control of the fundamental building blocks of all physical things. This field is likely to change the way we design and manufacture computers, vaccines, automobiles, and many other products. To encourage innovation, Dr. Baheti described NSF's Research Experience for Teachers (RET) Program, which supports a primary or secondary teacher's direct experience in a research laboratory or similar research environment. The program connects a teacher with a researcher, who can supplement an existing NSF grant or initiate a new one to obtain teacher support. Researchers are encouraged to involve teachers in funded research. The NSF program encourages transfer of new knowledge to pre-college classrooms and provides support for both teacher enhancement and the development of educational materials for the K-12 classroom.

## SIDEBAR: Past Speakers and Topics

This series of workshops has benefited from a group of exceptional speakers, and researchers in control systems and mathematics. Past talks have included:

“Using Mathematics for Epileptic Seizure Warning,” Ivan Osorio, M.D., Director, Comprehensive Epilepsy Center University of Kansas Medical Center, and Mark Frei, Ph.D., Operating Manager and Technical Director, Flint Hills Scientific, L.L.C.

“Music, the Brain, and Complex Adaptive Systems: Using Musical Metaphors and Models to Study Brain Functions,” Bryan Haaheim University of Kansas, and Deron McGee, University of Kansas.

“Brownian Motion: Past and Present,” Tyrone E. Duncan, University of Kansas.

“How the Internet and Wireless Networks are Controlled: What’s Happening behind the Scene,” P. R. Kumar, University of Illinois at Urbana-Champaign.

“Control of Jet Engines,” Richard M. Murray, California Institute of Technology.

“Powerful Ideas in the World of the Child,” Alan Kay, Disney Fellow and Vice President of Research and Development, The Walt Disney Company.

“Making Calculus Fun: How to Entertain at Parties,” Colin Adams, Williams College.

“Systems, Control, and Mathematics,” Stephen Boyd, Stanford University.

“How Feedback Changed the World,” Dennis Bernstein of the University of Michigan. This talk resulted in the articles “Feedback Control: An Invisible Thread in the History of Technology,” *IEEE Contr. Sys. Mag.*, Vol. 22, pp. 53-68, April 2002, and “Introducing Signals, Systems, and Control in K-12,” *Contr. Sys. Mag.*, Vol. 23, pp. 10-12, April 2003.

## SIDEBAR: Comments from Students about the Workshop

Numerous rewarding comments were received from participants after the workshop, including:

“What a wonderful day. My students were all greatly impressed with the level of knowledge presented, the achievements of the young students, and the many ways that math could be applied. Of course, the soccer team was the favorite, but among my students it seems that most of the presentations were a favorite with a smaller group of students. Education is a very hard sell so the kind of exposure you offered our students was most welcome. Thank you again for the invitation.”

“It was wonderful. The students had wonderful things to say about the speakers we heard. Thank you for taking the time to arrange this very worthwhile event for us.”

“The trip to the Workshop had a lot of information that at first seemed to not appeal to a middle or high school student. After a short time, with the excellent treatment from the hosts, it promised to be a beneficial experience. I enjoyed, and found interesting, all of the presentations, although some were beyond the middle or even high school level. When presenters were lecturing students at the high school level, we could immediately see the wonders of what they were talking about to us. We saw everything from futuristic cars to ingenious displays of mechatronics. We could instantly see the application to our education and what there is in the future. Of course, being interested in math and science, we could even imagine ideas of fascinating creations beyond what was presented.”

“The workshop was the most memorable and successful event. It was truly a collaborative effort of so many people.”

“I do not know how to find the words for how wonderful my trip was—I learned SO much and am forever grateful. As I write this, I am also working on a number of lesson plans based on the information I learned. You did an amazing job with the full-day workshop. I know how much work those are and have organized them myself. On the whole, I felt that the students took away a lot of newly found enthusiasm for engineering. Now, that enthusiasm has to be cultivated by their teachers. I am working on condensing my notes into an outline form and will email it to you once I am done. Feel free to share it with the other teachers if you’d like to. I would love to help you put on your next one so please, keep me in mind! I could certainly put together some pre and post activities and assessments and would enjoy doing it.”

## **SIDEBAR: Comments from the Maui District School Superintendent**

The following comments were received from Allen Ashitomi, Maui District School Superintendent:

Dr. Bozenna Pasik-Duncan, I am glad you received such an overwhelming response. I am really interested in science, and I believe we need to develop that component of our curriculum. I started in electrical engineering and then switched to education, but my heart is in the sciences. I am intrigued with the developments in genetics and astronomy. I'm still trying to understand string theory. Do you have a simple explanation? I again want to thank you for offering this opportunity to students in our school system.