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Development of a Soccer-Playing Robot for ROBOCON '94: An Example of Hands-on Education in Mechatronics Engineering*

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A hands-on project entitled 'Development of a Soccer-Playing Robot for ROBOCON '94' was conducted at the University of California, Davis, as an example of efficient and effective education in mechatronics technology. ROBOCON is an international robot design contest held annually in Japan. The robot was designed and fabricated by the students using state-of-the-art engineering technologies and tools. In so doing, the students learned and gained experience in practical technologies currently utilized in modern manufacturing industries. Ten undergraduate engineering students, representing mechanical, computer, electrical, and aeronautical engineering programs, worked intensively for 6 months to bring the robot to realization. The robot was a unique system that consisted of a lightweight frame structure and mechanisms integrated with a highly sophisticated, microprocessor-based control system, which was programmed in high-level language. The system successfully competed in ROBOCON '94 and received the Design Idea Prize from the university professors, engineers from industry, and officers of academic societies who made up the ROBOCON Committee.

INTRODUCTION

MECHATRONICS technology—a technology which seeks to integrate a simplification of mechanisms with a sophistication of electronics control—is one of the key subjects in a modern engineering education. In order to cope with the great demand in industry for engineers well versed in mechatronics technology, the methodology of mechatronics education has been studied [1] and the courseware for its education has been developed [2]. In order to meet this demand, the Department of Mechanical and Aeronautical Engineering at the University of California, Davis established a program in mechatronics in 1991. The goal was to train mechatronics engineers capable of solving interdisciplinary design optimization problems using evolving mechatronics system technology. As Fig. 1 shows, conventional mechanical system (pure mechanics) have evolved by making use of electric and electronics technologies to enhance the total system value, i.e. the performance and functionality per unit cost. The elements which have contributed to adding value to the system are classified into four categories: mechanics, general electric and electronics (including microelectronics, power electronics and microprocessors), software, and application-specific electronics firmware. Mechatronics technology can be regarded as a new systematized technology to achieve a breakthrough in mature pure-mechanical technologies.

These days, most machines (consumer and industrial) are equipped with mechatronics technology and the demand in the mechanical industries for engineers who can handle electro-mechanical technology is high. The University of California has been making an effort to produce such engineers to cope with the demand.

Since this is an application-oriented technology, hands-on training is crucial to supplement traditional lecture-based instruction. An undergraduate student project was introduced in 1994 to explore mechatronics technology. The goal of the project was to develop a robot for competition in ROBOCON '94. This paper describes the concepts behind the robot design, fabrication techniques of the robot mechanism, design of the integrated control system, and the results of the project.

BACKGROUND, RULES, AND REGULATIONS FOR ROBOCON '94

ROBOCON is an annual event which was established in Japan in 1990. The concept is for undergraduate engineering students to build robots and compete with one another. Judging is based not only on performance, but also on overall design quality. The aim of the competition is to interest young people in technology and engineering, specifically in the area of mechatronics. Moreover, it

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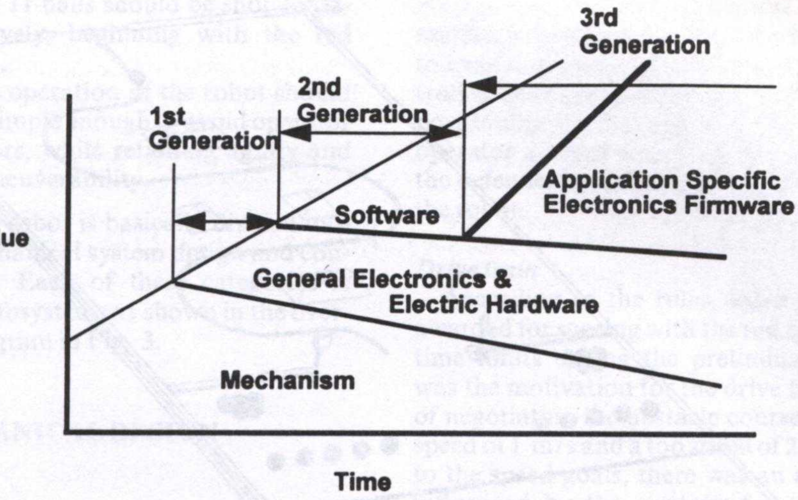

Fig. 1. Evolution of mechatronics.

encourages them to consider mechatronics engineering as a possible program of study at a university and ultimately as a career choice. In order to reach the public effectively, the competition is televised internationally and during Japanese prime time. By the end of March each year, new specifications for the robot are given to the universities by the committee. At this point, the students may begin work on the conceptual design of the robot. The design proposals need to be documented and submitted to the committee. By the end of May, the evaluations are complete, and those teams that have been accepted are notified. The acceptance rate, based on the evaluation of documents, is usually about 50%. After receiving notification of the acceptance, each team must build its robot by the end of August, as the competition is held on the first Sunday in September. The competition is videotaped and edited by Japan's largest television broadcasting company, Nippon Hoso Kyokai (NHK). It is subsequently televised as a 2 hr program throughout Japan on September 15, which is a Japanese national holiday.

The theme of the robot for ROBOCON '94 was 'Techno Soccer II'. A self-propelled, mobile robot had to be designed to first negotiate an obstacle course while operating in 'autopilot' mode. After that, the operator could assume control and proceed to collect 21 soccer balls and shoot them into a goal. All this had to be done within a time limit of 3 min. The robot had to be completely 'fly-by-wire', meaning that muscle power could not be used in any way. Furthermore, the robot design was subject to very specific limits on weight, size, power sources and total cost.

There were several major highlights regarding the rules for ROBOCON '94. Besides requiring the robots to be 'fly-by-wire', the rules were set up so as to give an overwhelming advantage to robots which operated on 'autopilot'. Those teams which relied solely on manual control had little chance of winning. The power source for each robot was prescribed as three lead-acid batteries of a particular model and brand. Each battery was rated 12 V, with a 2 A-hr capacity, when discharged over 10 hr. The robot's weight could not exceed 35 kg. The maximum dimensions at the start of the contest were 1.2 m × 1.2 m, with no limitations on height. The total material cost of the robot could not exceed 150,000 Japanese yen (approximately US$1500). The operator's weight had to be greater than 50 kg. The competition consisted of two parts: a preliminary contest and a final tournament.

Figure 2 shows the playing field. For the preliminary contest it was divided into several zones: the starting zone, the running zone, the shooting zone and the off-limits area. The starting zone was marked by a 1.2 m × 1.2 m square, out of which the robot was not allowed to extend once the competition had started. The red ball was placed just in front of this zone. A guideline 60 mm across and black in colour was painted on the white floor of the running zone to help robots avoid the four obstacles. Alternative aids for 'automatic control' consisted of an ultrasonic beacon and rotating lamp, each placed on poles at opposite ends of the running area. These poles, which measured 30 mm × 30 mm × 600 mm high, stood at either side of the shooting zone entrance. Since the placement of the obstacles was known in advance, it was possible to program the robot's motion during the autopilot mode without relying on any of these aids. A wooden fence bounded the competition area and also formed the border between the running area and shooting zone. The goal itself was 1.2 m wide and 1.5 m high. Internationally standard no. 5 soccer balls, with artificial leather coverings, were used. The ball dribbled through the obstacle course was red, while the remaining balls in the shooting zone were yellow. The 10 yellow balls were arranged into two lines of five balls each, running parallel to the goal. As the robot entered the shooting zone,

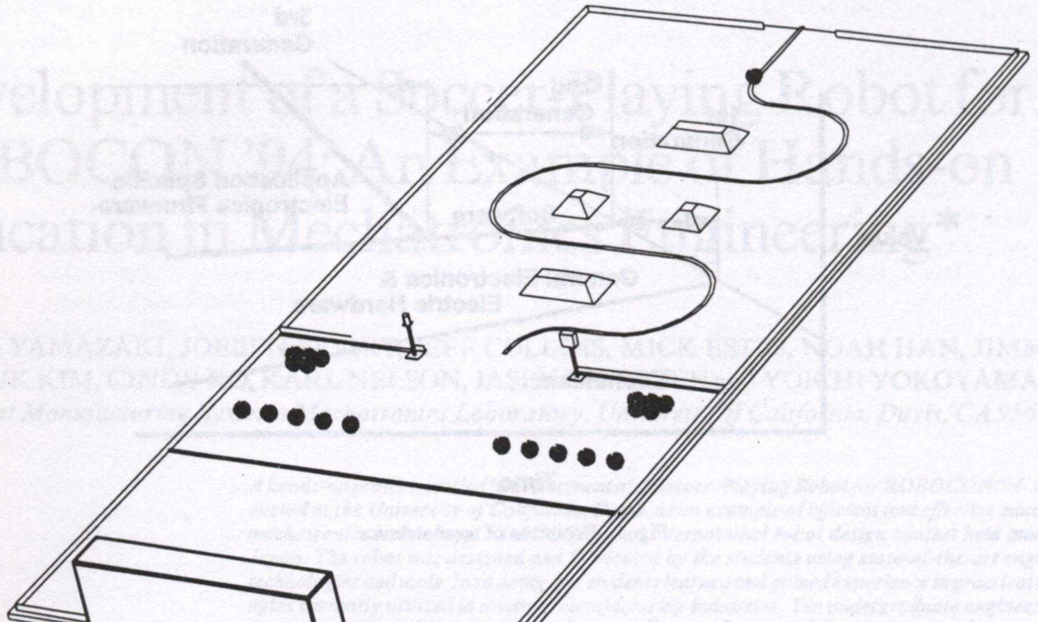

Fig. 2. Course layout.

one line lay to the left, and the other to the right. Each ball was placed in a small depression in the floor.

After navigating the obstacle course, using either manual control or autopilot, the operator assumed complete control of the robot. The robot was required to shoot the red ball before it could shoot any of the yellow balls. When shot within 1.5 min, the red ball scored 5 points; otherwise, it scored only 3. For robots without autopilot, the red ball scored only a single point. All yellow balls were worth one point apiece. The four top-scoring robots advanced to the tournament round. In the event of a draw, preference was given to the robot who had used autopilot.

The final tournament was a head-to-head competition among four teams. This resulted in two semifinal matches and a single final match. The teams used the same robots as in the preliminary round, and the course was much the same. The only differences were that the goal was widened to 3.6 m, and 10 additional balls were available. The tournament involved the opposing teams alternatively defending and attacking. Each match was divided into two 3 min rounds, with a 3 min interval in between. Each round began with the attacking team negotiating the obstacle with the red ball. The defender was restricted from defending the goal until 1 min had elapsed. The number of balls was augmented by the addition of two clusters of five balls each. The attacking team could not intentionally target the opposing driver or robot. Naturally, the team which scored the most points won. A tie would have been won by the team that had scored the first ball in the lesser amount of time.

These rules, as set forth by the ROBOCON Committee, established a number of specific guidelines that all competing robots were required to satisfy. Just as every engineering design begins with an understanding of the design constraints, the first task was to understand the rules and regulations for ROBOCON '94.

MAJOR DESIGN GOALS

With the official rules to hand, it became possible to set out specific design goals and approaches to designing the robot. These goals addressed such issues as dribbling the red ball, navigating the obstacle course in autopilot model, maneuvering the robot, collecting the balls, and shooting them.

Strategy

Based on discussions about strategy, the following design goals were established:

Dribbling: The ball would be restrained by the collection roller.

Autopilot: The robot's path through the obstacle course would be preprogrammed. Deviations would be sensed by velocity sensors attached to the drivetrain.

Ball collection: After entering the playing field, the red ball will be taken in, followed by the remaining 10 balls. This means 21 balls should be stored in the robot structure.

Ball shooting: The 11 balls should be shot consecutively, beginning with the red ball.

Maneuvering: The operation of the robot should be simple enough to avoid operator errors, while retaining agility and maneuverability.

The design of the robot is basically divided into two categories: mechanical system design and control system design. Each of these categories is broken down into subsystems as shown in the overall system block diagram in Fig. 3.

MECHANICAL DESIGN

Frame

Due to the large number of components that needed to be mounted in a limited space, the frame had to allow as much flexibility as possible for the placement of these components. A simple frame design would not only minimize weight, but would also allow for easy fabrication. Another goal was to maintain sufficient strength in order to support the operator, who weighed at least 50 kg.

Shooting

The primary goals of the shooting assembly were to project the balls at high speed and in as rapid succession as possible. Approximate ball velocities of 8 m/s were expected. The firing rate was to be greater than one ball per second. To minimize the number of controls the operator would be required to handle, the aiming of the shooters would be controlled by the orientation of the robot. The shooter positioning on the side of the robot allowed the operator a better opportunity of shooting around the defender by utilizing the fore and aft motion of the robot.

Drive train

According to the rules, extra points would be awarded for scoring with the red ball within certain time limits during the preliminary contest. This was the motivation for the drive train design goals of negotiating the obstacle course with an average speed of 1 m/s and a top speed of 2 m/s. In addition to the speed goals, there was an acceleration goal influenced by the strategy for the head-to-head competition. The placement of the shooters coupled with a large lateral acceleration offered the ability to rapidly sidestep the defender during the final tournament.

Collection/storage system

The design goals for the collection system were simple: to pick up and store all the balls and transport them to the shooters in the least amount of time. A difficulty arose in the collection of five ball clusters, which required the collector to be at least three balls wide. The collector also had to allow for misalignment by the operator and still gather the balls at a reasonable rate. Furthermore, the collec-

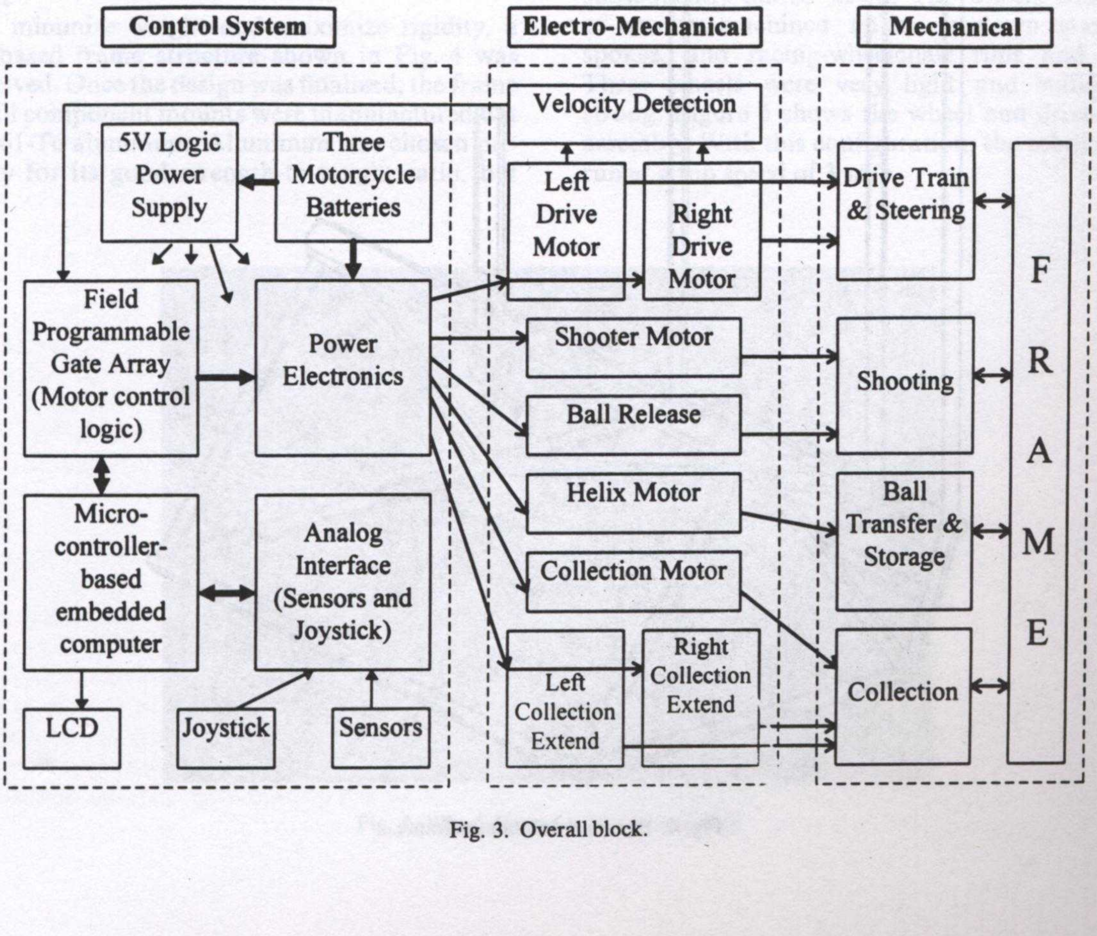

Fig. 3. Overall block.

tion system had to store at least five balls until they were transferred to the storage device with a capacity of 21 balls. Picking up and storing all the balls allowed the shooting time to be maximized. In order to store the entire group of balls it was necessary to have a mechanism that was capable of rapidly and reliably lifting the balls to a height of 1.5 m.

CONTROL SYSTEM DESIGN

Hardware

This category encompassed the microcontroller-based embedded computer, the application interface and the power electronics needed to physically implement the control system. To make the motor control circuitry easily reconfigurable, this was implemented in a field-programmable gate array. Because of overall weight and size limitations, the electronics hardware, including sensors and power electronics, needed to be as compact as possible. Since power was also in very short supply, the digital logic and power electronics had to consumer a minimum of power. Moreover, the control hardware had to tolerate noisy power supplies that were evident when the motors were running.

Software

While software essentially takes up no mass on the robot, this is ultimately what controls it. Since

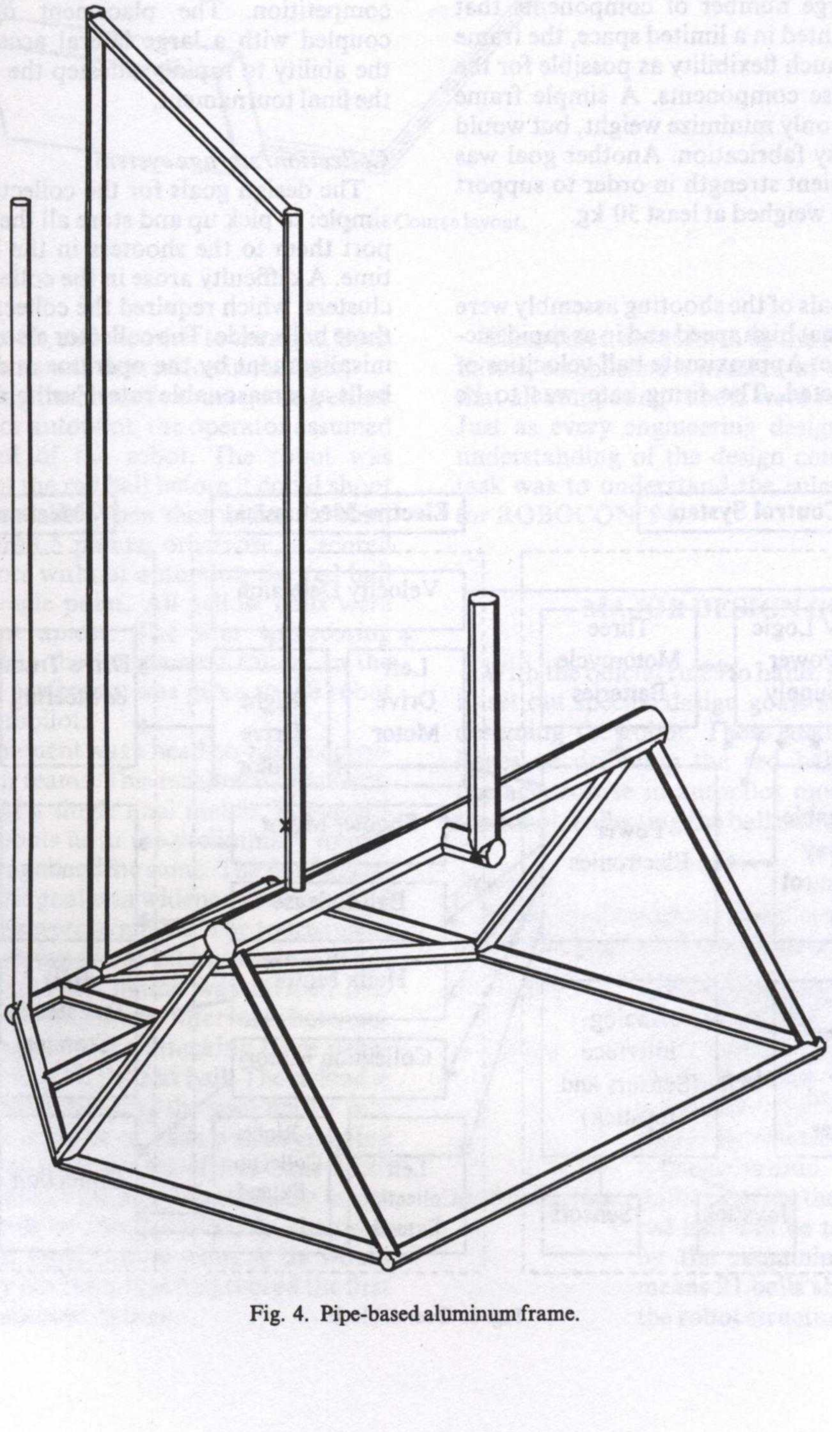

Fig. 4. Pipe-based aluminum frame.

the control hardware was kept fairly simple, most functions were left for software implementation. Because of the reliance on software and in-circuit reprogrammable hardware, there was a great amount of flexibility in configuring the system. In all, the robot was a true software-based 'fly-by-wire' system. In addition to the regular control software, system set-up and diagnostic software was implemented to address the problems of calibrating and testing the robot prior to the contest. The high-level language C was employed during software design to simplify programming and enable the use of sophisticated software techniques, such as cooperative multitasking.

MECHANICAL DESIGN AND MANUFACTURE

Design tool

I-DEAS, a solid-based, three-dimensional integrated computer-aided engineering software package, was utilized effectively in the design process. Due to the robot's complexity, this type of CAD system was necessary to visualize the configuration of the robot and the placement of the components within its volume. Solid modeling made it unnecessary to construct physical models prior to the design specification. In spite of its many advantages, problems arose during the modeling process that could not have been anticipated. The CAD software was also utilized to make preliminary calculations of the weights of various components.

Frame

To minimize weight and maximize rigidity, a pipe-based frame structure shown in Fig. 4 was conceived. Once the design was finalized, the frame and all component mounts were manufactured out of 6061-T6 aluminum. Aluminum was chosen primarily for its good strength-to-weight ratio, but ease of machining was also a consideration. The structural members were 0.035 in. aluminum tubing. The frame and all mounts were tungsten inert gas (TIG) welded. The transportation of the robot from Davis, California, USA to the competition site in Osaka, Japan was another issue that had to be addressed. Most airlines would have frowned upon the package necessary to house the fully assembled robot (1 m wide × 1 m deep × 1.5 m high). An important feature of the frame was its ability to be quickly and easily disassembled and reassembled for shipping purposes.

Drive train and steering

Besides minimizing weight, the drive train was also designed to maximize the robot's velocity, acceleration and maneuverability. In order to achieve these ends, a two-wheel drive system with auxiliary support wheels was adopted. Each drive wheel was equipped with a high-power, high-torque drive motor, such that steering could be performed by controlling the differential rotation of the two motors. The motors used were originally intended for use in an automotive electric power-steering application. The significant weight of the motors was reduced by remanufacturing the cast iron motor end-caps from aluminum using CNC machining. Twelve-to-one reduction gearboxes were employed to convert the high torque of the motors to achieve the design speeds. These gearboxes were purchased off the shelf and were modified to suit this application. The mounting plate was deemed overbuilt and overweight, and was subsequently milled down. The wheels consisted of custom-machined hubs, cut-down standard spokes, and racing-wheelchair rims and tires. These wheels were very light and sufficiently strong. Figure 5 shows the wheel and drive train assembly. With this configuration, the robot could run at a top speed of 3 m/s.

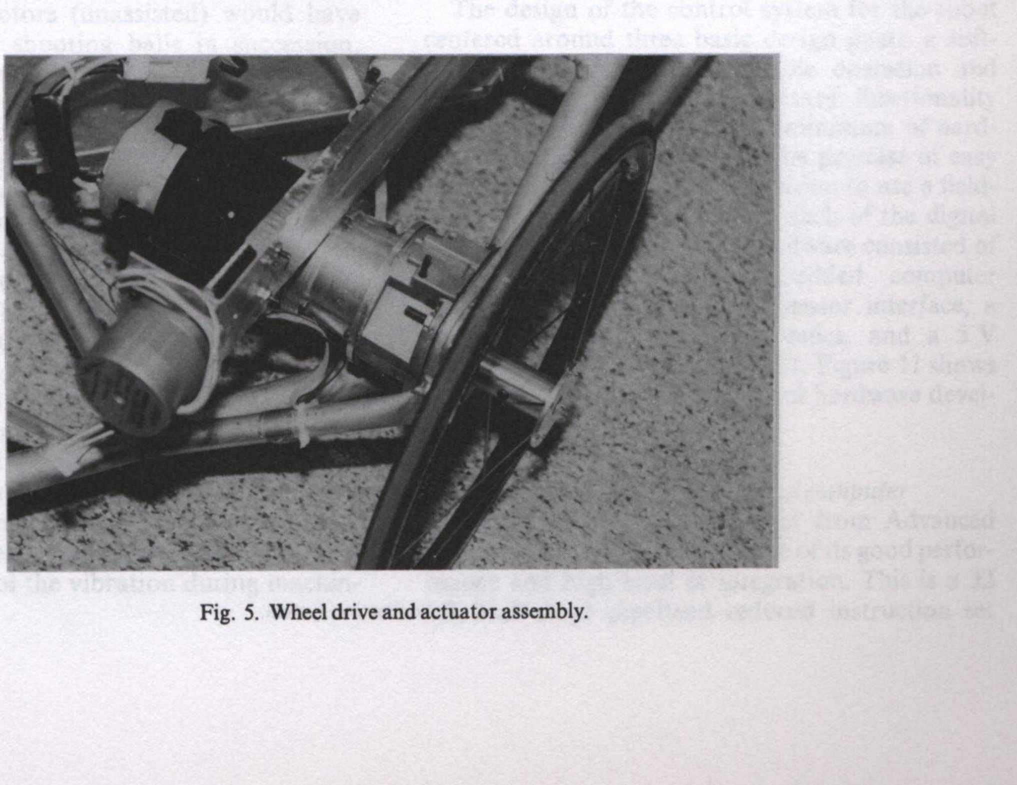

Fig. 5. Wheel drive and actuator assembly.

Collector

The system to collect the balls from the playing field consisted of three distinct subsystems. These were the motorized, extendable roller; a ramp; and a motorized helix lifter. Not surprisingly, weight proved an important consideration for all these components as well.

The roller was constructed from a perforated aluminum tube wrapped in foam, and was driven by a high-torque, low-speed motor. Stepper motors driving worm gears were used to control precisely the amount of extension along the tracks on which the roller assembly was mounted. The extendable tracks allowed for the three necessary positions of the roller: fully retracted, fully extended and operational. The fully retracted position was necessary to satisfy the size limitation at the onset of a run. The fully extended position was used to trap the red ball and dribble it through the course under automatic control. Finally, the operational position enabled the roller to pick up balls.

The roller, which forced the balls up a specially designed ramp, enabled ball pick up. The first stage of the ramp was the same curvature as a soccer ball. The next stage was a downward sloped platform that guided the balls into an opening at the base of the helix. The platform was designed to store at least five balls until they could be transported to the storage device. The ramp was 36 in. wide, 42 in. deep, and roughly pentagonal in shape. The ramp was manufactured by forming and pop-riveting 0.020 in. aluminum sheet metal. This material was chosen because of its low density and ease of formability. However, sheet metal does not possess the necessary rigidity. To address this issue, some of the same stock was bent, riveted and attached underneath the ramp. This effectively formed a closed-section reinforcement, which dramatically increased overall rigidity. Figure 6 shows the collector in its final form.

Ball transfer and storage

After being collected, the balls were then transferred into the storage device. Its design consisted of aluminum tubing, bent into a winding channel running from the top of the robot to the shooting mechanism. The mechanism that lifted the balls from the ramp, straight up the rear of the robot, and to the entrance of the storage system was a rotating helix. This, incidentally, led to the name 'The Helix' for the completed robot. The design of the helix was anything but trivial, since the design goals specified an elevation rise of 1.5 m/s and a transfer rate of one ball per second. To accomplish this, the helix was driven by a low-speed, high-torque motor at 1 r.p.m. The helix and associated riser tubes also served as structural members of the frame. The spine of the helix was 1 in. diameter, 5 ft. long aluminum tube, while the riser tubes were 3/4 in. diameter aluminum tubes. Fifty-two aluminum tubes, each 3/8 in. in diameter and 7.5 in. long, formed the surface of the helix. This length was chosen so that the contact point would lie under the ball's center of gravity. The surface was laid out by following a helical line along the circumference of the spine. A hole was drilled in the spine every inch along this line. The surface tubes were mounted into the holes so that they butted against the opposite side of the spine. Thus, these tubes effectively formed the surface of a helix. The rotation of the helix resulted in a vertical force that served to elevate the soccer balls. However, the inclination of the surface, at the contact point, resulted in a horizontal force which caused friction between the balls and the riser tubes. To reduce this to acceptable levels, polymeric Iglide sleeve bearings were used at the end of each of the helix tubes. These sleeve bearings allowed the ball to roll up the riser tubes instead of sliding. Figure 7 shows the entire ball-lifting mechanism.

After the helix had elevated balls into the storage,

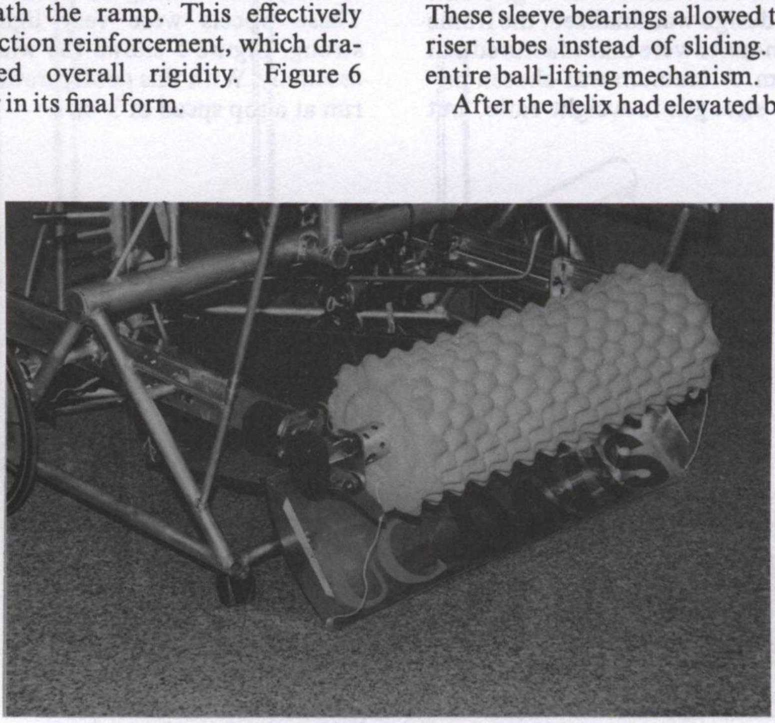

Fig. 6. The collection system.

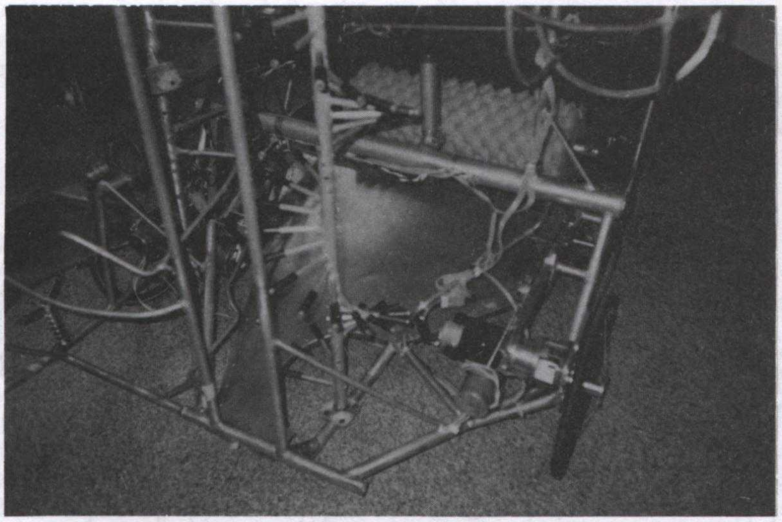

Fig. 7. The ball-lifting mechanism.

gravity caused the balls to roll toward the shooters. The storage consisted of a system of guide rails made of thin aluminum tubing. There were two particular strengths to this design. First, it was very light, considering the extent of the storage system. Also, a tube bender allowed the tubes to be easily shaped, permitting a variety of possible geometries. Thus, it was a relatively simple matter to accommodate all the other components of the design.

Shooter

The basic design of the shooters was inspired by softball pitching machines, which use a spinning wheel to accelerate the ball. However, there were several important differences. First, the relative size and mass of the ball to the spinning wheel is much smaller in softball machines than in this soccer ball application. Also, there were severe power and weight limitations. As a result, the chosen shooter motors (unassisted) would have been incapable of shooting balls in succession, while maintaining acceptable ball velocities. Given these conditions and limitations, a shooting mechanism consisting of two shooter wheels and an attached flywheel was designed.

The flywheel was designed to have minimum weight, yet still have substantial rotational inertia. Thus, the majority of the flywheel's mass was concentrated at the furthest radial points. The flywheel weighed 2 lb, and had a diameter of 13 in. At its design speed of 2500 r.p.m., it was capable of shooting 21 balls at acceptable ball velocities, at the design firing rate. However, the rotational accuracy necessary for a 13 in. diameter flywheel spinning at these speeds could only be achieved using CNC machining. Furthermore, in order to achieve a web thickness of 1–2 mm, a special mounting apparatus had to be fabricated and damping materials were necessary to control the vibration during machining.

CNC machining was also utilized for fabricating the 2 mm thick shooter wheels. The design sought to minimize flex, weight and size, while distributing stress uniformly. The wheels were arranged in the assembly so that they each contacted the ball at 45 with respect to the horizontal plane. This allowed for the ball to center easily between the wheels, and thus contact evenly with little error or slippage. The shooter wheels were mounted from above in order to impart topspin on the ball during contact. In addition to topspin, the shooter assembly compressed the ball during contact. The compression spring minimized slip between the ball and shooter wheels, and also imparted a slight upward velocity to the ball, increasing overall flight time. Figure 8 shows a CAD rendering of the shooter assembly and Fig. 9 shows an actual shooter.

Control hardware

The design of the control system for the robot centered around three basic design goals: a software-definable interface, reliable operation and ease of debugging. The necessary functionality needed to be obtained using a minimum of hardware. This desire, along with the promise of easy reconfigurability, led to the decision to use a field-programmable gate array for much of the digital circuitry. In all, the control hardware consisted of a microcontroller-based embedded computer (MBEC), a user interface, a sensor interface, a motor interface, power electronics, and a 5 V supply circuit for the logic circuit. Figure 11 shows the block diagram of the control hardware developed.

Microcontroller-based embedded computer

An Am29200 microcontroller from Advanced Micro Devices was used because of its good performance and high level of integration. This is a 32 bit, four-stage pipelined reduced instruction set

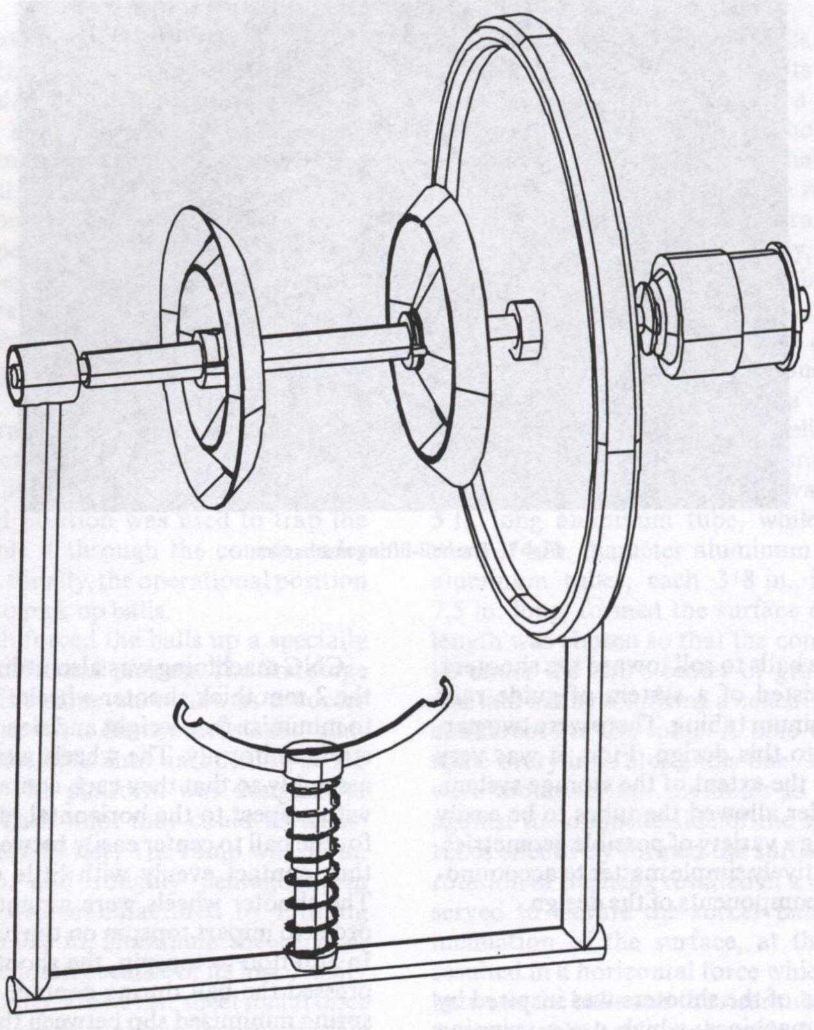

Fig. 8. Rendering of the shooting assembly.

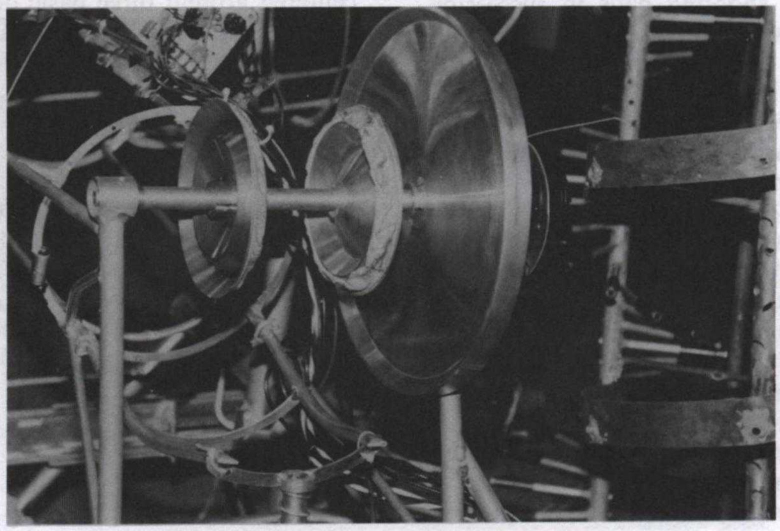

Fig. 9. The shooter assembly.

computer (RISC) processor. Rather than design the memory and serial interfaces from scratch, an AMD SA29200 demo board was used. Integrated on a single 3 in. × 3.5 in. printed circuit board are a 16 MHz Am29200 microcontroller, 1 Mbyte of dynamic random access memory (DRAM), a serial port, 512 kbytes of erasable programmable read-only memory (EPROM), and expansion headers for the easy addition of other peripherals.

User interface

To ensure that the robot would operate smoothly, in contrast to many of the robots in the previous year's contest, an analog joystick was incorporated into the design. To give the driver ample visual feedback while piloting the robot, a 4 line × 16 character LCD display was also included in the design (Fig. 10). The LCD also proved to be a valuable tool in setting up control parameters and debugging software. It served as a computer monitor, in contrast to the many embedded systems which have only a few LEDs to aid in debugging code.

The I/O board was designed to implement these functions, plus act as the sensor interface. 7400 AC series logic chips were used to implement most such digital functions. The I/O board was designed to attach to the expansion headers of the MBEC board, and lie on top of it. Since the robot's design had not yet been finalized, the I/O board was designed with extra hardware so that extra devices could easily be interfaced. Thus, the board included a generous amount of sensor interfacing, in the form of a four-channel analog to digital (A/D) converter, a dual eight-channel analog multiplexer (A-MUX), and two four-channel comparators with digitally programmable thresholds. It also included two general-purpose, 8 bit output ports. Miscellaneous glue logic, as well as power and sensor connectors were included as well. The I/O board was fabricated in-house as an extremely dense, two-sided PCB.

Motor interface

The most basic function of the control system is precise motor control. Variable speed control of the DC motors was achieved by using pulse width modulation (PWM). Generating PWM and control signals for the motor pre-drivers required specialized hardware. To make this circuitry easily reconfigurable, it was implemented using a field-programmable gate array (FPGA). An FPGA is an extremely versatile programmable logic device, which can efficiently implement any combinatorial or sequential digital logic design. Moreover, since the particular FPGA adopted (the Xilinx XC4005) is based on a static RAM technology, it is completely in-system reprogrammable. Since new logic configurations could be loaded at any time, design changes to this subsystem did not necessitate desoldering or changing the physical electronics hardware.

The hardware and software needed to interface the FPGA to the MBEC board were subsequently designed. For reliability and compactness, a PCB was designed to connect the FPGA to the expansion connectors on the MBEC and the header connectors going to the motor pre-driver circuits. Like the I/O board, this PCB was designed and manufactured in-house at a cost of under $10. The Xilinx board fitted underneath the MBEC board, and was connected to the data, address and control buses of the microprocessor. After the MBEC began executing the robot program, it immediately executed the necessary sequence of commands to program the PFGA. Once this was done, the program running on the MBEC could access the FPGA as though it were a part of memory. All such logic designs were entered and simulated using the Powerview digital design suite, and compiled using the Xilinx XACT FPGA compiler.

Power electronics for motor control

Two heavy-duty automotive motors were selected for the drive train of the robot. They

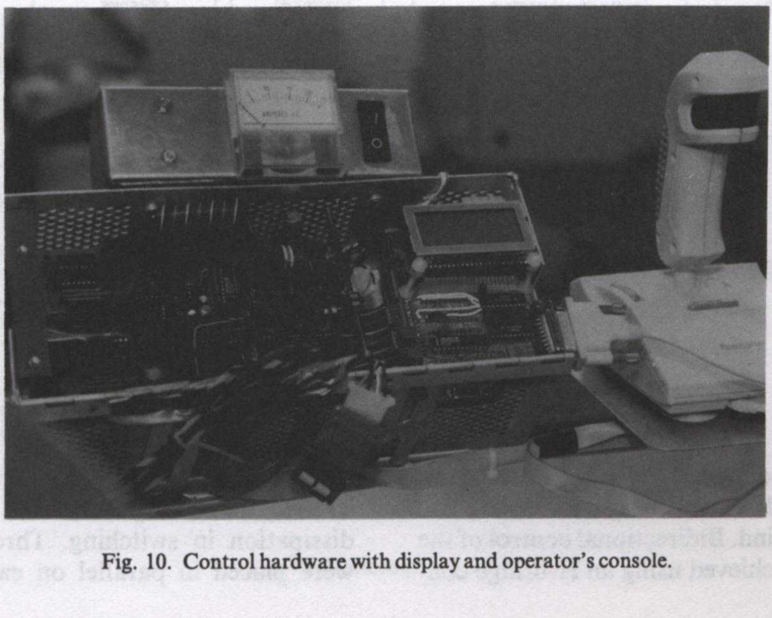

Fig. 10. Control hardware with display and operator's console.

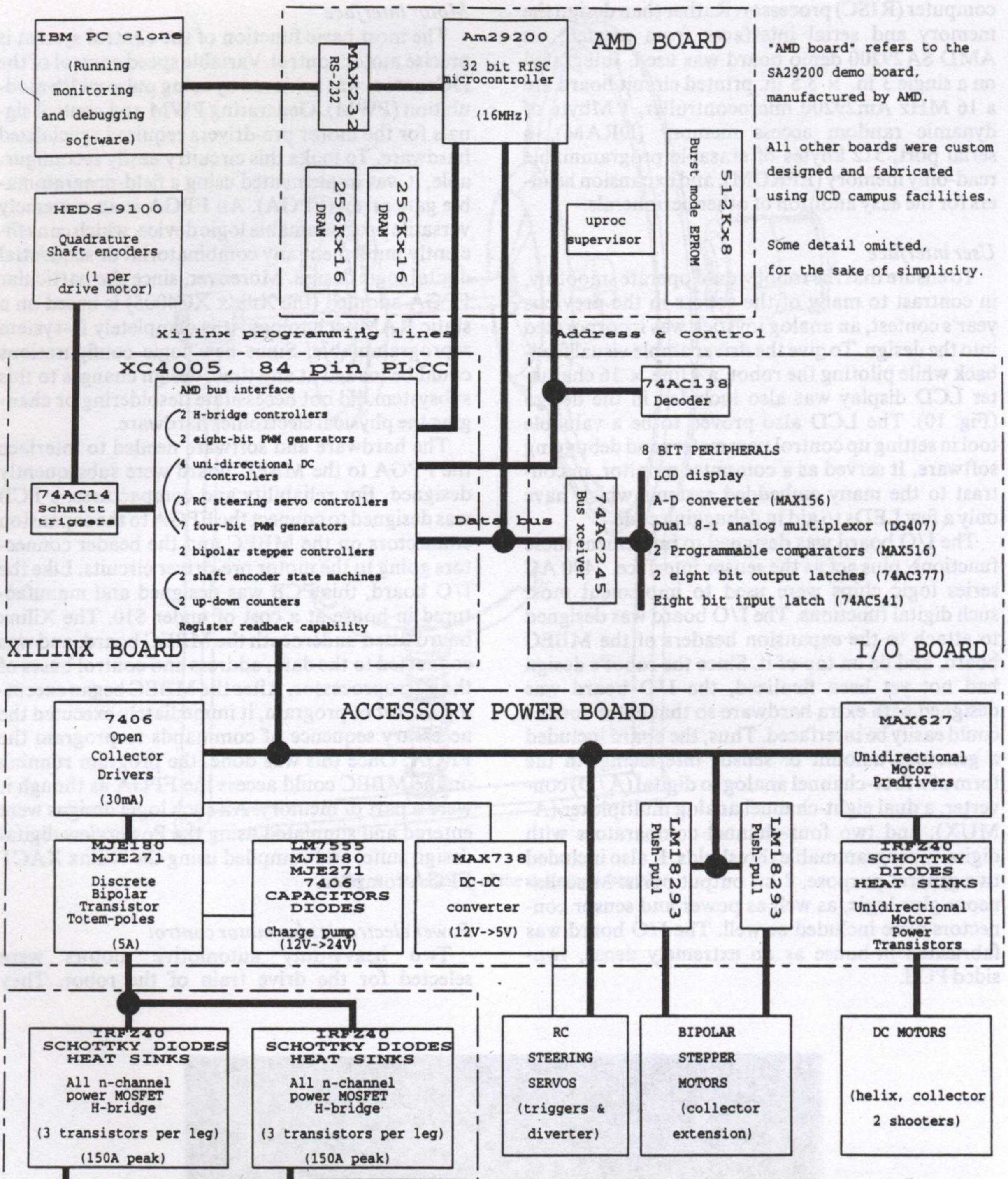

Fig. 11. Architecture of control hardware, including power electronics.

proved difficult to control, as the power electronics had to be designed with their maximum current draw of 120 A in mind. Bidirectional control of the drive motors was achieved using an H-bridge configuration. n-channel metal-oxide field effect transistors (MOSFETs) were used to minimize power dissipation in switching. Three such transistors were placed in parallel on each leg of both H-

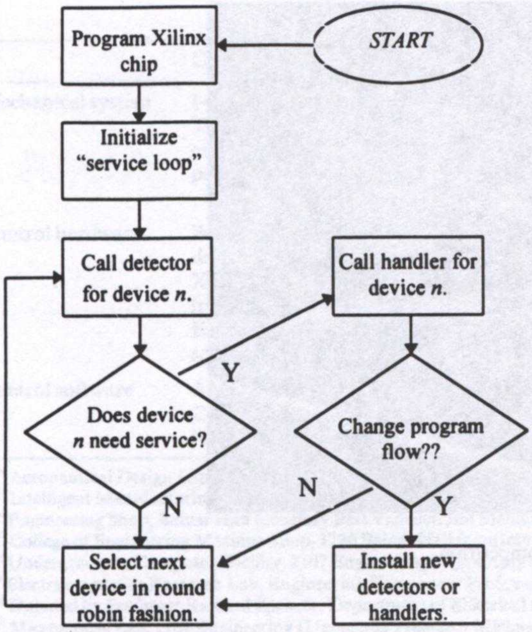

Fig. 12. Software flowchart.

bridges, resulting in a 150 A peak switching capacity. Since n-channels were used in a high-side configuration, a charge pump circuit, capable of generating a voltage 11 V higher than battery voltage, was needed. A PCB was made to implement the two H-bridges, one for each drive motor. Figure 11 shows the block diagram for all the power electronics.

The final PCB was designed to drive the gates of the MOSFET's for the main drive motors and to switch the various accessory motors. After a failed attempt to use integrated circuit MOSFET gate drivers to control the main H-bridges, the revised design resorted to discrete NPN and PNP bipolar transistors. These were arranged in a totem pole configuration and proved an effective way to drive the highly capacitive MOSFET gates. The helix, collector and shooter motors each required only a single n-channel transistor, as these motors were only under unidirectional control. The stepper motors used to extend the collection roller were each controlled by push–pull power IC's. The RC steering servos used for the ball releases needed only a single control line coming off the FPGA, and thus no additional hardware.

Logic power supply

The final, yet important, circuit was the logic voltage supply. The MBEC, Xilinx and I/O boards all ran at 5 V. The contest rules imposed a limitation of three motorcycle batteries, of 12 V apiece. These were connected in parallel to maximize the amount of current that could be drawn. Thus, battery voltage needed to be converted to 5 V. Although the standard method was to use voltage regulators and appropriately large heat sinks, a far superior approach had been tried: DC to DC converters. Instead of simply burning the extra power as heat (as in a regulator), a DC–DC converter performed a true power conversion, and efficiencies exceeded 90% (i.e. only 10% of the power is given off in electromagnetic noise or heat). This provided up to 750 ma at 5 V, at input voltage as low as 6 V. It required several external components, and a pi filter to smooth switching noise. A second such circuit was placed on the accessary power board, powering both the circuits there and the 5 V RC steering servo motors. Figure 10 shows the control hardware with display and operator console.

CONTROL SOFTWARE

The intention from the outset was to leave the close-loop motor control to the software running on the MBEC. The FPGA would generate the

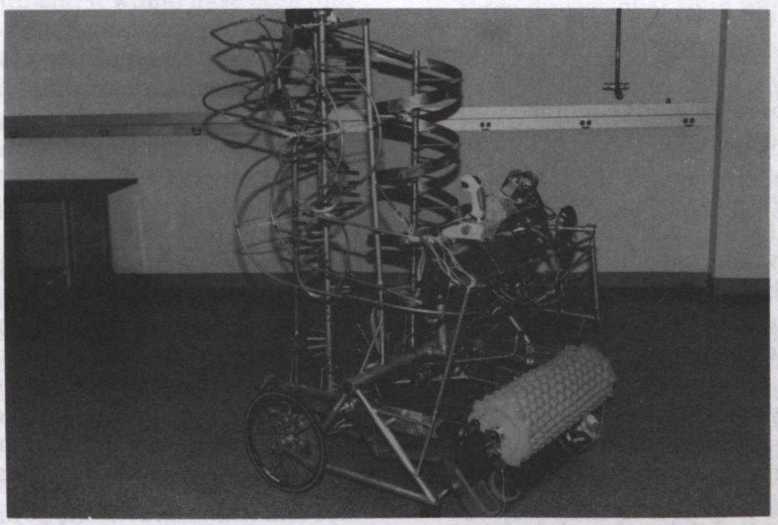

Fig. 13. The completed robot.

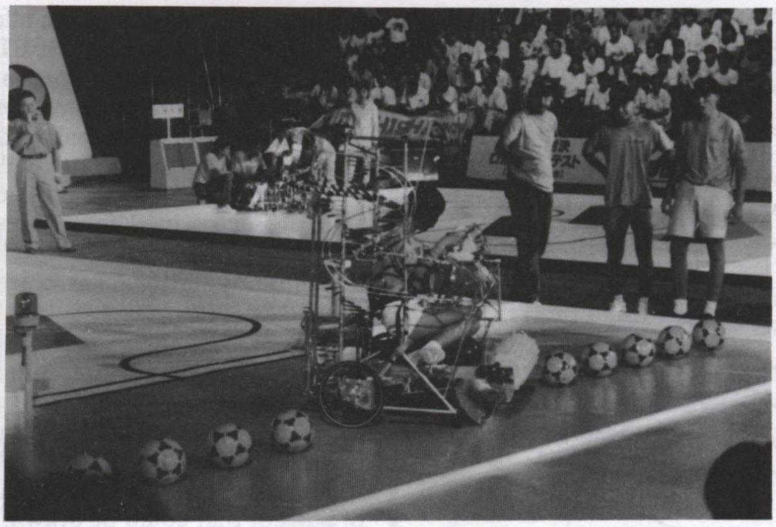

Fig. 14. The robot in competition.

PWM signals necessary to modulate the power given to two drive train motors. It also had counters to keep track of the pulses coming from the shaft encodes to detect the velocity of the robot. The software had to interpret this feedback and determine the appropriate power allocation to the motors. To accomplish this, standard control systems theory was employed. Each drive motor was controlled by an independent proportional, integrating, derivative (PID) controller. This type of controller ensures that the DC motors respond as expected, even under varying load, acceleration and battery conditions. The control gains were adjusted properly in a heuristic manner to achieve the fastest response without loosing control stability. The actual code to perform this computation was extremely simple. A vastly larger amount of code went into making the control parameters easily adjustable by the user and doing various low-level and miscellaneous tasks.

Figure 11 shows the architecture of the control system. The program, as shown, was responsible for the variety of tasks needed to successfully control the robot. Among these, the most time-critical routine was the closed-loop PID motor control. Other tasks included servicing the A/D converter to read the joystick, checking for the joystick buttons, servicing the various open-loop motors, and writing characters to the LCD display one at a time. Naturally, it would have been inconvenient and impractical to have constantly been forced to explicitly call routines to perform these services. Therefore, it was decided to use a cooperative multitasking system. A main service loop (analogous to the operating system) cycled through all the known 'devices'. It asked each one, in turn, if it needed service. If it did, it called the appropriate service routine, with the applicable parameters. Program flow was altered by changing detector and service routines. Naturally, since there are always devices that need service, it became imperative that nothing dominate the processor.

As described under the hardware section, the LCD display effectively served as a small computer monitor. The joystick, originally intended only for operator's control of the robot in the 'fly-by-wire' setup, also proved a valuable debugging tool in lieu of a keyboard. A menuing system was developed that made use of the LCD and joystick. On power up, the user was presented with a list of options on the LCD screen. The joystick was used to move up and down and select the appropriate options. The available options included adjusting the PID constants, starting various phases of the contest and performing various system tests. Notably, the flexibility afforded by the menuing system and the various options implemented therein completely eliminated the need for separate test programs.

INTEGRATION AND EVALUATION

The successful completion of the project required the interdisciplinary coordination of all 10 team members. The team worked in parallel to arrive at the goal of a completed robot by the date of the competition. The nature of the work and the facilities available for each group required the mechanical group and the control group to remain relatively isolated from each other for much of the time. True integration of the system began after the majority of the robot was completed. Before then, the control group had been testing the control of various components 'on the bench'. Although the bench testing was valuable to the development process, the integration with the mechanical components of the robot was the ultimate test.

Upon arrival at the contest site in Osaka, the robot system was reassembled and tested. Most of the functions provided the target performance.

Table 1. Major tools used in the project

	CAD/software tools	Computer platforms	Fabrication tools
Mechanical system	I-DEAS, solids-based 3D computer-aided engineering software package	Sun SPARCStation 10 Unix workstations[a] Hewlett-Packard 712-80 Unix workstations[a]	Mazak Four-axis CNC lathe[b] Mazak CNC milling center[b] Extensive conventional machine tools, including mills, lathes, and drill presses[c,d] TIG welding equipment[c,d]
Control hardware	Powerview digital design suite XACT logic compiler for Xilinx FPGAs Easytrax PCB design software	Hewlett-Packard 712-33 Unix workstations[e] IBM PC clones, 486 class[h]	Ultraviolet light table[f] Photographic PCB etching equipment and chemicals[g] Various tools and equipment[h]
Control software	AMD/Metaware high C optimizing compiler for 29K architecture	IBM PC clones, 486 class[h]	

[a] Aeronautical Design Lab, 3063 Bainer Hall (courtesy Department of Mechanical and Aeronautical Engineering).

[b] Intelligent Manufacturing Systems/Mechatronics Lab, 1229 Bainer Hall (courtesy Professor Kazuo Yamazaki).

[c] Engineering Shop, Bainer Hall (courtesy Bert Vanucci, Jim Mehlschau, Jerry Dill *et al.*).

[d] College of Engineering Machine Shop, 1220 Bainer Hall (courtesy Dave Hook).

[e] Undergraduate Computer Facility, 2107 Engineering II (courtesy of the Department of Electrical and Computer Engineering).

[f] Electromagnetics Research Lab, Engineering II (courtesy Professor Rick Branner, Department of Electrical and Computer Engineering).

[g] Donated by Professor Richard Spencer, Department of Electrical and Computer Engineering.

[h] Micromouse Lab, 1107 Engineering II (courtesy Professor Michael Soderstrand, Vice-Chair, Department of Electrical and Computer Engineering).

Other acknowledgements: Alan McKillop (MAE Department, Chair), Ben Ransom (MAE computer guru), Denyse Miller (MAE purchasing).

However, several uncontrollable factors did have a significant effect on the robot's performance. The single most troublesome problem was the painted surface of the contest balls. The storage system was prone to jamming because the surface of the painted contest balls was significantly stickier than the surface of ordinary soccer balls. The tackiness of the balls also caused feed problems into the mouth of the helix at the collection and in the helix itself. These problems were addressed at the contest site by slightly modifying the storage and helix entrance geometries. The robot was successfully completed and demonstrated in the competition (Figs 13 and 14).

The project spanned about 6 months, including the entire summer vacation. Because of the large weekly time commitment, it would have been difficult for students to complete such a project during the school year. The students gained a great deal of knowledge and practical experience, of a type that cannot be obtained from a traditional classroom learning environment. One estimate of the work time devoted to this project was 4000 person-hours. Time-concentrated work was a key to the successful completion of this project. That is to say, because of the fixed amount of time needed to prepare and clean up, longer work days proved more time efficient. According to the students involved, this project gave them an enormous amount of integrated knowledge about mechatronics systems. In particular, this robot proved an exercise in code-signing a mechanical system and a modern, microprocessor-based, high-level programmed control system. As an important facet in an effective mechatronics education, this project was a great success. Table 1 shows the major tools used for each subsystem.

CONCLUSIONS

To provide practical education in mechatronics engineering, a sizable project was formed and conducted by 10 undergraduate students at the University of California at Davis. The project was to design, fabricate and demonstrate the robot by attending the ROBOCON '94, an international competition for soccer-playing robots.

The conclusions are as follows:

1. Many of the design goals for the robot arouse out of a careful analysis of the ROBOCON '94 rules.
2. The robot system was designed as an integrated system consisting of both a mechanical system and a control system.
3. The mechanical system was designed using a three-dimensional solid model CAD system to allow discussion on possible design alternatives, given the geometry constraints.
4. The designed robot was a unique aluminum-pipe frame-based structure. It had many optimized parts, including necessary actuators and sensors. Certain critical parts were most effectively fabricated using sophisticated CNC machining.
5. The control system was designed in a modular fashion, and included state-of-the-art embedded controller technology, field programmable gate arrays and power electronics. All in all, an easily reconfigurable system was built, with a minimal chip count hardware.
6. For versatility, the control software was designed and implemented so that all robot motions were fully controlled by software. The development of a simple, but powerful, multitasking software system aided in real-time control. A menuing system made calibration easy

and eliminated the need for separate test programs.

7. A simple but convenient man–machine interface was implemented by employing a single-arm analog joystick and mini-LCD display for simple robot operation.
8. The robot was built and demonstrated successfully in the contest. The design idea prize was awarded by the ROBOCON '94 Committee.

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Jeff Collins is currently a senior student at the Department of Computer Engineering, University of California, Davis. His major interest is microelectronics custom design and fabrication. He worked on the microcontroller design for the soccer robot and control software development.

Mick Estes is currently a senior student at the Department of Mechanical and Aeronautical Engineering, University of California, Davis. His major interest is mechanical system design. He designed and fabricated the basic structure of the soccer robot.

Noah Han is currently a senior student at the Department of Mechanical and Aeronautical Engineering, University of California, Davis. His major interest is mechanical system design. He worked on the design of the ball collection, storage and transfer mechanisms of the robot.