Super Armatron

An Inexpensive, Microprocessor-Controlled Robot Arm

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Five degrees of freedom, low cost, microcomputer control, accurate repeatable positioning, and usefulness—these features all describe the robot we built in the Wright State University laboratories. Our goal was to build such a robot and have it perform a desired task. Our robot, called Super Armatron, started out as the Tomy Armatron robot. Originally distributed by the Tomy Corporation, the inexpensive Armatron is now available in Radio Shack stores around the country.

Our definition of functional included position sensing and computer control of each joint. These two features allow Super Armatron to perform complex tasks under program control. Super Armatron is equipped with a teach-mode capability and a simple, three-instruction robot language for moving the arm.

The Arm. As purchased, the Armatron arm is moved with two joysticks, which control the five axes of motion and open and close the gripper. Photo 1 shows Super Armatron after we completed the initial hardware modifications. We removed the joystick controls and replaced them with solenoid actuators. Both the solenoids and the Armatron are mounted on an aluminum plate. We added Hall-effect sensors to the waist, shoulder, elbow, wrist, and gripper. An optical encoder determines wrist roll positioning.

A single DC motor located in the base provides the motive power for the entire arm. Each joint is controlled through a series of plastic gears and metal rods. Although the waist joint is capable of 360-degree rotation, we limited this motion to 180 degrees to protect the added electrical wires. The shoulder joint moves up 25 degrees and down 40 degrees, while the elbow joint moves 90 degrees to the left or right.

The elbow joint is coupled to the wrist so that when the elbow moves to the left, the wrist rolls counterclockwise (as seen from the elbow) and vice versa. Cross-coupling also occurs between the wrist's pitch and roll axes. The wrist rolls counterclockwise when the pitch axis (limited to ± 90 degrees) moves up, and clockwise when the pitch axis moves down. Although the wrist can roll 360 degrees, we limited its motion to ± 180 degrees to prevent damage to the wiring harness.

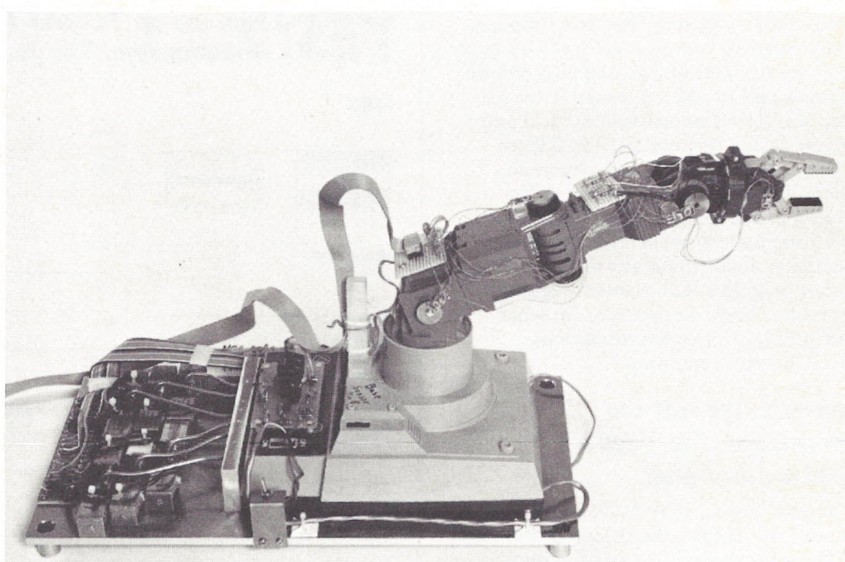

Photo 1. Super Armatron after hardware modifications. Twelve solenoid actuators control the five axes of motion and the gripper. Hall-effect sensors provide position feedback for the waist, shoulder, elbow, wrist, and end-effector gripper. The plexiglass rod by the waist joint prevents the waist from rotating a full 360 degrees, which would pull off the Hall-effect sensor wiring harness.

The Computer. The computer system consists of a PDP-11/23 running the RT-11 operating system that is connected to an LSI-11 to which the compiled programs are downloaded. The control program is written in Micropower Pascal and uses several prewritten I/O driver routines coded in assembly language.

The LSI-11 contains analog-to-digital converters with four decimal digit accuracy for sensor input, and a parallel I/O (PIO) board for communicating with Super Armatron and its 12 joint-control solenoids.

The Software. The three basic arm movements are: move from point A to point

B; grasp; and release. We decided that the arm would always start at a known point before beginning a task. We use the teach-mode to move one joint at a time until the arm is in the desired starting position, and then store the sensor readings for that point. The teach-mode makes the arm highly adaptable to any application.

The program is designed to store up to 50 points. The "teacher" is responsible for ensuring the arm has a clear path from one point to another, since obstacle avoidance is not built in. After a series of stopping points are stored, the program is placed into the run mode. The arm moves to the starting point and proceeds through the preplanned movements.

Due to the power considerations of simultaneously moving multiple joints, we decided to move only one joint at a time. For any one step, the waist joint moves first, and movement proceeds outward towards the wrist. This decision also simplified the control program.

The task we wished to complete was the Towers of Hanoi game. We chose this application since it is familiar to most computer science students. We used three rings, which makes for only 12 stopping points. Figure 1 shows the eight different disk configurations encountered while solving the puzzle. The main program in listing 1 shows how the disks are moved.

Three points were defined on each of the three poles and one point above each pole. To move the first ring, the arm moves from the starting position to a point above the first pole (point 4) with the gripper open. The arm then moves to point 3, grasps the first ring, continues back to point 4, continues to point 12, and down to point 9, where it releases the ring and completes the first move. Similar move cycles continue until all three rings are on the third pole. To prevent the arm from hitting any obstacles, we instructed the arm to move to the "holding" position above each pole before moving to the next position. Photo 2 shows Super Armatron executing the programmed task.

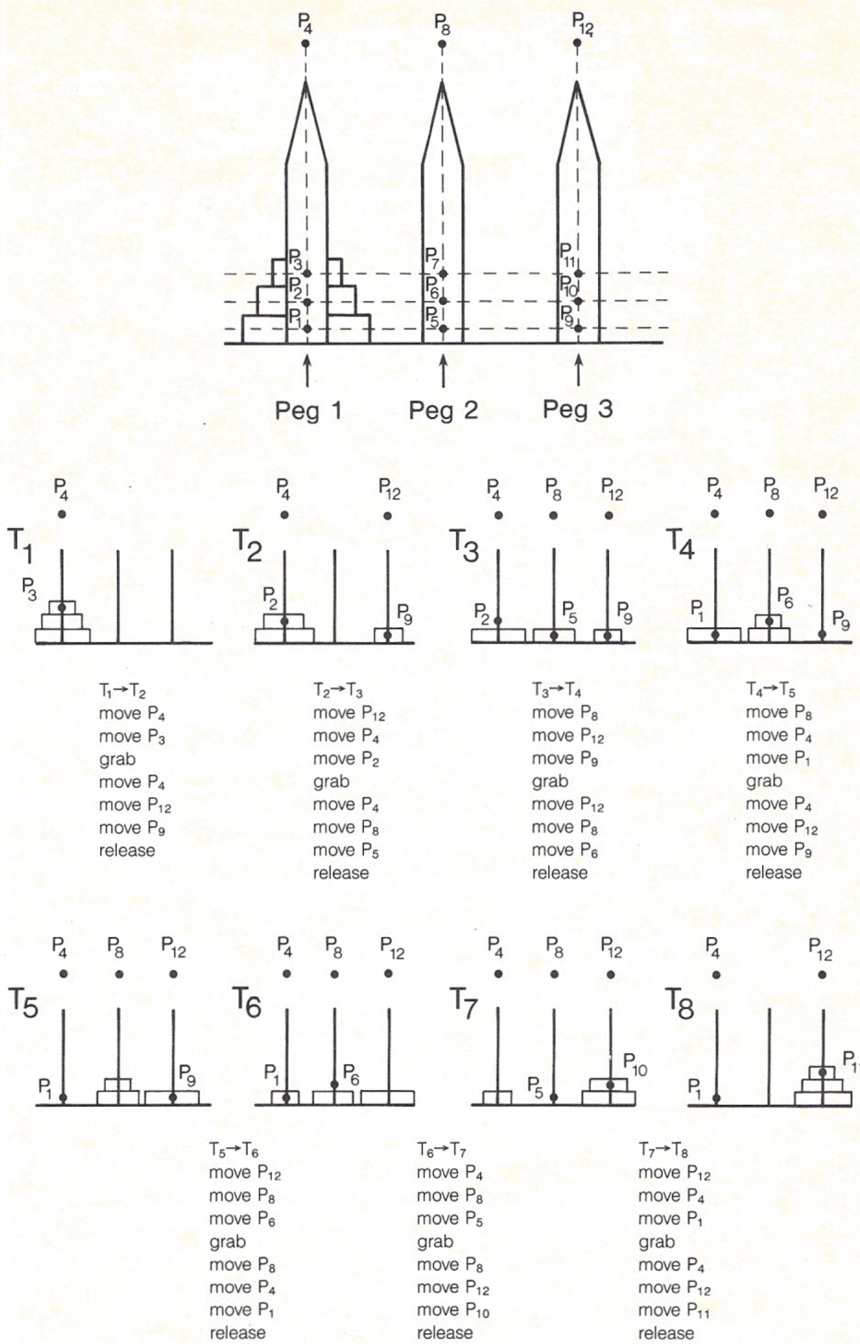

Figure 1. The Towers of Hanoi problem is used to illustrate the robot control language. This task requires accurate position sensing and movement during the execution of the 55 commands needed to complete the game. When using the robot control language, the operator must define only the 12 predetermined positions (P1 through P12) and the order in which the rings must be moved between them. The main progam listing shows how the moves are made.

The Control Language. The program in listing 1 contains all of the procedures used to control the arm. The prewritten I/O routines are not included since they are hardware dependent.

The first section of the program contains all of the necessary tables and variables. Table POS TABLE is used to store the Hall-effect sensor readings for each stopping position. The vector JCW is the Joint Control Word, which is sent to the PIO board to control joint motion. The associated comments describe the joint motion attached to the solenoid number.

In Micropower Pascal, all procedures must be defined before they are invoked. We will explain the procedures (MOVE, GRAB, RELEASE, and TEACH) in the order in which they appear.

The MOVE procedure moves the arm, one joint at a time, starting with the waist. The position to which we want the arm to move is compared to the current position. Since the Hall-effect sensor on the waist

```
PROGRAM ROBOT (INPUT,OUTPUT);
        TYPE     VECTOR = ARRAY [0..15] OF BOOLEAN;
        TYPE     TABLE = ARRAY [0..50,0..15] OF INTEGER;
        VAR      J,MOV,JOINT,DIRECT,KEEP_MOV,STORE,I,POS,K : INTEGER ;
                 GPOSMIN,GPOSMAX,HEMI,OLDHEMI,POSMAX,HFLAG,STOP,INISTOP : INTEGER;
                 GPOS,WPOS,SPOS,EPOS,PPOS,RPOS,WWPOS : INTEGER ;
                 FINALPOS,ROLL1,ROLL2,NEW_ROLL1,NEW_ROLL2 : INTEGER;
                 JIN,WR_JOINT : INTEGER;
                 A,B,AN,BN,S1,S2,S3,S4,S1N,S2N,S3N,S4N,CU,CD : BOOLEAN;
                 HA,HB,OLD_WCOUNT,WCOUNT,HIVALUEA,HIVALUEB : INTEGER;
                 JCW : VECTOR ;
                 POS_TABLE : TABLE ;
        PROCEDURE WRTPIO (JCW : VECTOR);EXTERNAL;
        PROCEDURE INIPIO ; EXTERNAL;
        FUNCTION GETADC (S, D : INTEGER) : INTEGER; EXTERNAL;
        FUNCTION RDPIO : VECTOR;EXTERNAL;
        PROCEDURE CORR_WRIST ; FORWARD;
        PROCEDURE WR_COUNTER ; FORWARD;

        THE FOLLOWING PROCEDURE WILL BE THE TEACH MODE FOR THE ARMATRON
        ROBOT.

                 SENSING POSITION OF THE ARMATRON


       14-PIN CABLE                        A/D CABLE
  AXIS    PINOUT      CONNECTED TO    PINOUT     SIGNAL

SHOULDER    1         CONNECTED TO      3        CH 1
ELBOW       2         CONNECTED TO      5        CH 2
PITCH       3         CONNECTED TO      7        CH 3
ROLL4       4         CONNECTED TO      9        CH 4
ROLL5       5         CONNECTED TO     11        CH 5
GRIPPERS    6         CONNECTED TO     13        CH 6
WAIST       8         CONNECTED TO     15        CH 7

  IN ADDITION:  7(GND)  CONNECTED TO   18        AMP L


                 READING WRIST ROLL USING PIO


       14-PIN CABLE                        PIO CABLE
  AXIS    PINOUT      CONNECTED TO    PINOUT     SIGNAL

ROLL4       4         CONNECTED TO    J1-37      A I/O 0     (LOWER SENSOR)
ROLL5       5         CONNECTED TO    J1-39      A I/O 1     (UPPER SENSOR)

  IN ADDITION:  7     CONNECTED TO    J1-26      GROUND

NOTE:  FOR CORRECT OPERATION OF THE PIO BOARD, J1-22, "USER RDY B", MUST BE
       CONNECTED TO GROUND (J1-26).



        SOLENOIDS ARE ACTIVATED WITH A LOW INPUT.

CONVENTION:
WAIST, ELBOW:  VIEWED FROM ABOVE.     ROLL:  LOOKING INTO GRIPPERS.


                     16-PIN CABLE                        PIO CABLE
SOLENOID   MOVEMENT        PINOUT       CONNECTED TO    PINOUT       SIGNAL

   0       SHOULDER DOWN     1          CONNECTED TO    J1-14        B I/O 0
   1       SHOULDER UP       2          CONNECTED TO    J1-12        B I/O 1
   2       WAIST CTR-CLKWSE  3          CONNECTED TO    J1-13        B I/O 2
   3       WAIST CLKWSE      4          CONNECTED TO    J1-11        B I/O 3
   4       ROLL CLKWSE       5          CONNECTED TO    J1-16        B I/O 4
   5       ROLL CTR-CLKWSE   6          CONNECTED TO    J1-9         B I/O 5
   6       PITCH DOWN        7          CONNECTED TO    J1-15        B I/O 6
   7       PITCH UP          9          CONNECTED TO    J1-10        B I/O 7
   8       ELBOW CTR-CLKWSE  10         CONNECTED TO    J1-4         B I/O 8
   9       ELBOW CLKWSE      11         CONNECTED TO    J1-1         B I/O 9
   10      GRIPPERS OPEN     12         CONNECTED TO    J1-7         B I/O 10
   11      GRIPPERS CLOSED   13         CONNECTED TO    J1-8         B I/O 11


           IN ADDITION:         8       CONNECTED TO    J1-26        GROUND

NOTE:  FOR CORRECT OPERATION OF THE PIO BOARD, J1-22, "USER RDY B", MUST BE
       TIED TO GROUND (J1-26).


                 STORE = 1 SELECTS POSITION TO BE STORED
                         0 DO NOT STORE POSITION
}
PROCEDURE MOVE(POS : INTEGER);



        {MOVE WAIST}

BEGIN
        WPOS := GETADC(7,1);
        POSMAX := WPOS;
        HFLAG := 0;
        IF WPOS <> POS_TABLE[POS,7] THEN
           BEGIN
              IF POS_TABLE[POS,8] = OLDHEMI THEN
                 IF OLDHEMI = 0 THEN
                    IF WPOS > POS_TABLE[POS,7] THEN
                        JOINT := 2
                    ELSE
                        JOINT := 3
                 ELSE
                    IF WPOS > POS_TABLE[POS,7] THEN
                        JOINT := 3
                    ELSE
                        JOINT := 2
              ELSE
                 BEGIN
                 HFLAG := 1;
                 IF OLDHEMI = 0 THEN
                    JOINT := 3
```

Listing 1. The robot control routines are written in Micropower Pascal from Digital Equipment Corporation.

does not provide absolute position, we must also know which "hemisphere" contains the next position. Depending on which "hemisphere" the next position is in, the arm is moved either clockwise or counterclockwise. The waist movement continues until the hemisphere and Hall-effect sensor reading match the values taken from the position table.

The shoulder is moved next. The direction is easily determined, since the Hall-effect sensor provides readings from a minimum to a maximum value throughout the range of movement. The elbow motion is started and allowed to continue until the values match.

The elbow movement direction is determined in the same manner as the shoulder direction. When the elbow is moved, however, we must consider the mechanical cross-coupling with the wrist. A wrist correction routine, which will be explained later, is also called.

The arm's pitch is adjusted in the same manner as the shoulder and elbow. Since the pitch movement also experiences a cross-coupling interaction with the wrist roll motion, the wrist correction routine is called. The final arm movement is wrist roll. Wrist roll positioning is determined using optical encoders. Basically, the wrist is rolled in the proper direction until a position counter matches the value stored in the position table.

Procedures GRAB and RELEASE simply cause the gripper to close or open. The gripper moves to a predetermined position defined by a special variable. Although our program uses a constant value, the value could be read from the position table. This change would allow the arm to grasp various sized objects while executing a single task.

The TEACH procedure begins by initializing the PIO board. The wrist is then rolled to the mechanical stop for its initial position. While the wrist is rolling, the high values obtained from the optical encoders are read and stored to provide a reference for future wrist roll movements. An arbitrary value of 100 is assigned to the roll count to prevent it from becoming negative.

Once everything is initialized, the TEACH program displays a menu of arm movements and allows the operator to move one joint at a time. The operator stops arm motion by pressing a switch, which is connected to an analog-to-digital converter. The operator can then decide either to store the current position or to continue moving

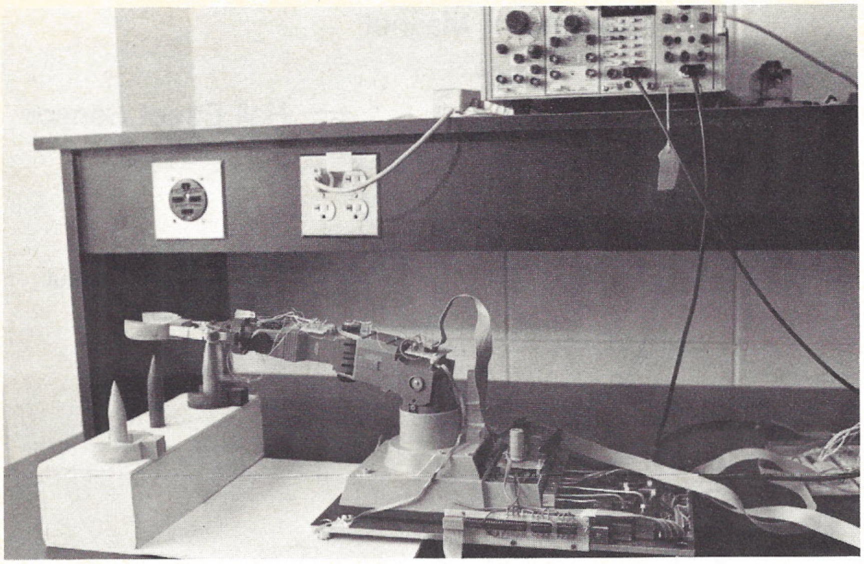

Photo 2. Super Armatron is programmed to complete the Towers of Hanoi game, implemented here using three rings. This game requires moving the three rings located on the first pole to the last pole. The rules are simple: move one ring at a time, and never place a larger ring on top of a smaller ring. Super Armatron is caught in the process of moving one ring to a new location.

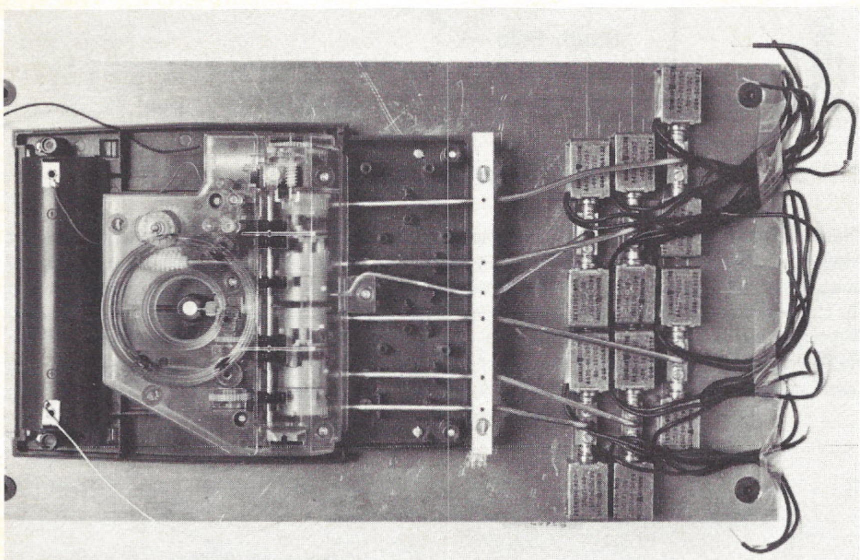

Photo 3. Top view of Super Armatron with the cover removed. All joints are controlled by one DC motor. Joint movement is achieved by activating one of the six pairs of solenoids. Two solenoids are required to control one joint resulting in two opposite motions. The solenoid pairs are mechanically connected with a metal plate.

the arm. If the position is to be stored, the operator must enter a value indicating the hemisphere in which the waist is positioned. The operator can then proceed to another position. When all the positions are stored, the TEACH procedure returns control to the main program.

The wrist correction procedure counteracts the undesirable cross-coupling of the wrist and elbow and keeps the wrist in its present position as the elbow or pitch is adjusted. The procedure works by watching the wrist counter value. If the wrist counter value changes by two, the elbow or pitch movement is stopped, and the wrist is rolled until the counter returns to its initial value. The elbow or pitch movement is then restarted.

The wrist counter procedure performs a set of Boolean functions on the wrist roll optical encoder inputs. Given the initial and next position of the wrist, a state table can be devised to ascertain the roll direction. The roll direction is then used to determine whether the roll counter must be incremented or decremented.

The main program calls either the TEACH, MOVE, GRAB, or RELEASE procedure. In the Towers of Hanoi game application, the movements are in a loop so that the game is played continuously. These four function calls provide the flexibility needed for many different applications. This main program, with only minor modifications, could be designed to repeat a wide variety of functions endlessly.

Additional Hardware. The arm's joint movements are controlled by an LSI-11 microcomputer, which actuates solenoids through a parallel output port. Joint position is sensed and fed back to the computer by Hall-effect transducers, which detect the orientation of a small, round magnet placed at each joint. Each Hall-effect sensor produces an analog output voltage, which is connected to one channel of a 12-bit analog-to-digital converter in the LSI-11. Since the roll axis could not easily be sensed with this technique, we implemented an optical shaft encoder using two TRW reflective object sensors.

Motion Control. Photo 3 is a top view of the Armatron base with the cover removed, exposing the modifications we made to provide for computer control. Each joint is controlled by stopping the rotation of one of the six plastic cylinders seen in the photograph. Each cylinder has five tabs around its circumference. The middle tab is for stop; the two tabs on the left provide two speeds in one direction; and the two tabs on the right provide two speeds in the opposite direction.

The LSI-11 controls the arm by actuating solenoids, which in turn move metal rods (fingers) that catch on the plastic tabs. This mechanization provides for one forward speed, one reverse speed, and stop. Each metal finger pivots on a pin in the metal block at the edge of the plastic base. We selected this method to allow room for mounting the 12 solenoids and to keep the solenoid stroke short.

Two opposing solenoids are required for each finger. A small metal plate connects their two plungers. Each solenoid has a spring around its plunger so that both plungers are out when the solenoids are off. This places the finger at the middle tab stop position. Actuating one solenoid moves the finger to a tab which engages a gear and produces motion about one joint. Actuating the other solenoid in the pair causes motion in the opposite direction. The controlling program must ensure that both solenoids are never actuated simultaneously, since the result is indeterminate.

The solenoids, which we obtained from electronic surplus for $1.50 each, are manufactured by Guardian Electric (part number A420-062057) and are intended for 18V operation. We actuated the solenoids with a 12V supply from a quad high current driver, ULN 2064NE. When actuated, the solenoid draws 200mA.

We added two mechanical stops to prevent damage to the wires connected to the arm. One stop is mounted on the base to prevent 360-degree rotation about the waist. The other mechanical stop is mounted on the wrist to prevent 360-degree rotation about this joint.

Sensing Joint Position. The orientation of the six joints in the arm must be measured to determine the arm's position. The joints are at the waist, shoulder, elbow, pitch of wrist, roll of wrist, and gripper. The first four joints and the gripper are sensed by measuring the field from a magnet mounted on the joint. The wrist roll is sensed using optical encoding techniques.

The magnet is a ¾-inch diameter Alnico 2 disk (Permag part number SD1701), magnetized as a two-pole rotor along the diameter. A 3/32-inch diameter hole is drilled in the middle. The sensor is a Micro Switch (part number 915512-2), linear output Hall-effect transducer, which requires a voltage between +8V and +16V. This transducer has three leads: Vcc, ground, and output. The sensor's output is Vcc/2 with no magnetic field. The transducer is mounted over the edge of the magnet, with about ⅛-inch clearance.

In this application, using a 10V power supply, the output voltage varies approximately sinusoidally with magnet angle of rotation from about 8V at one pole of the magnet to 2V at the other pole. Figure 2 shows the typical positioning of the Hall-effect transducer and voltage output as a function of the magnet angular orientation. The output of each Hall-effect transducer is connected to an input channel of a 0 to 10V, 12-bit analog-to-digital converter in the LSI-11.

Sensing Wrist Roll Position. The wrist has no location suitable for placing a round

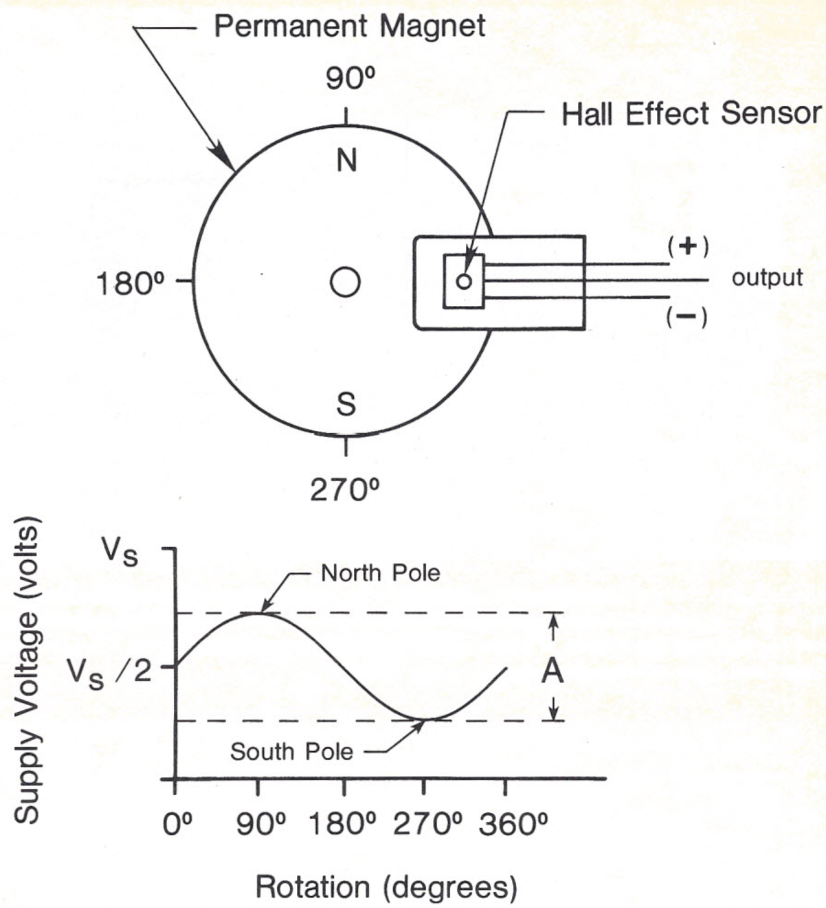

Figure 2. The Hall-effect sensors provide absolute position information if they are used within a dynamic range of approximately 180 degrees. The output voltage from 90 degrees to 270 degrees is continuous and unique. From 180 degrees to 360 degrees, however, the output voltage is not unique. It is necessary to position the magnets accurately for the joints with a limited range. Since the waist joint has a range greater than 180 degrees, we use the slope of the tangent line to determine the absolute position. The amplitude (A) of the Hall-effect sensor's output signal is a function of the magnetic field strength. The amplitude reaches a maximum when the Hall-effect sensor is positioned as close to the magnet as possible.

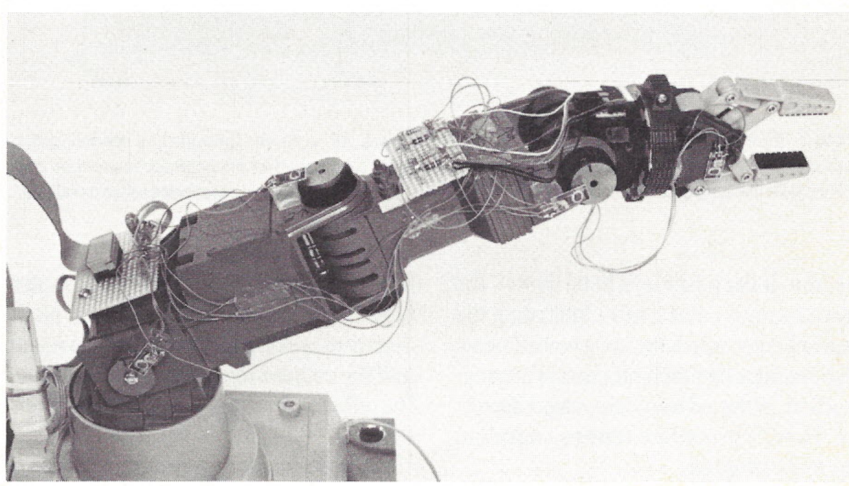

Photo 4. Hall-effect sensors and round magnets are carefully positioned so that each joint location provides a unique output voltage from the Hall-effect transducer. This goal required that the magnets be positioned so that the sensor never passes over either pole. This was achieved on all joints except the waist. Two optical encoders are used to sense wrist roll position. The two sets of alternating black and white patterns provide directional information and 32 positions per revolution.

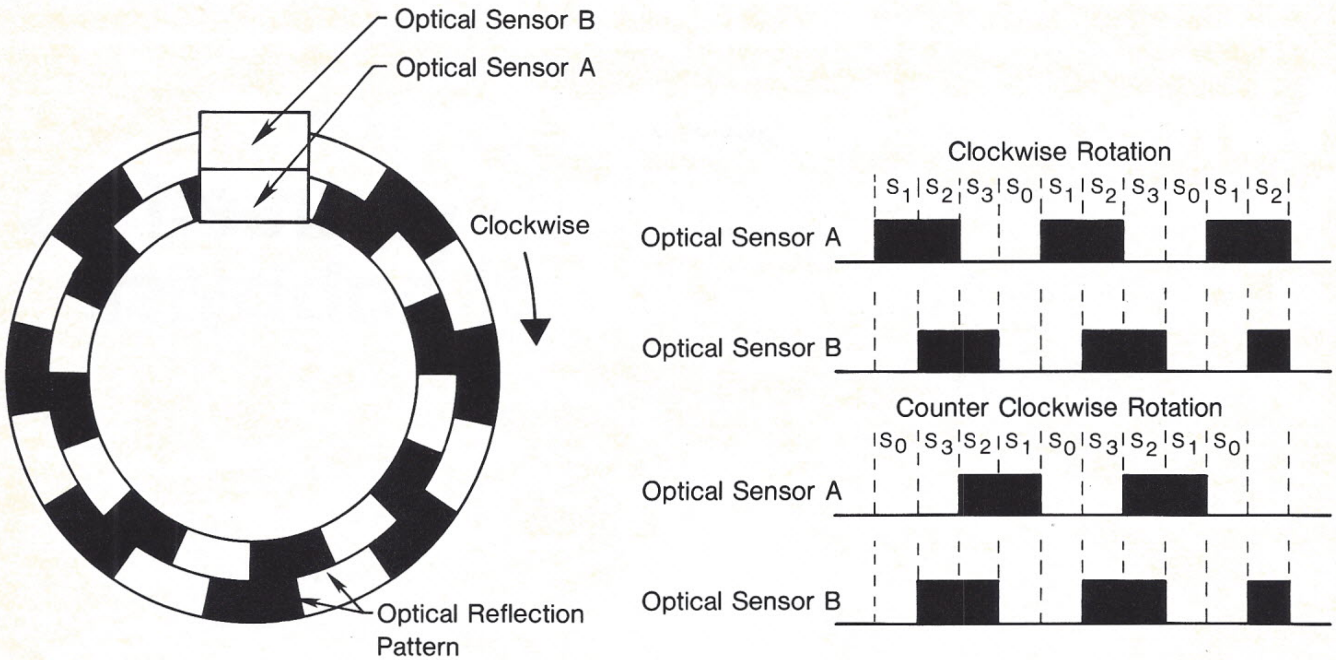

Figure 3. The optical reflection pattern on the disk causes the phototransistors in the light sensors to turn on and off. By using two sensors and offset reflection patterns, the outputs form four states. Clockwise rotation provides a count-up sequence, and counterclockwise rotation provides a count-down sequence. Because these sensors do not provide absolute position information, the state changes and direction of change are required to determine an absolute position.

magnet, yet requires reasonable positioning accuracy. We decided to use an optical shaft encoding technique for position sensing. We made a round paper ring to fit on the back rotating surface of the gripper assembly, as shown in photo 4. The paper is colored as shown in figure 3. The two concentric rings, each divided into 16 equal sectors alternating black and white, are offset by half a sector. Two TRW reflective object sensors (part number OBP 125A) were glued together, mounted on the pitch link, and aimed at the black and white disk, as shown in figure 4.

The sensors provide an electrical signal from a phototransistor which is amplified and made TTL compatible by using a Quad Norton amplifier (National Semiconductor part number LM 3900) as shown in figure 5. Although this signal can be fed into a parallel input port on a computer, we used two input channels on the already available analog-to-digital converter to read this data.

This shaft-encoding technique provides only relative position information. It provides for measuring direction of rotation in discrete increments of 11.25 degrees. Ab-

Continued on page 28

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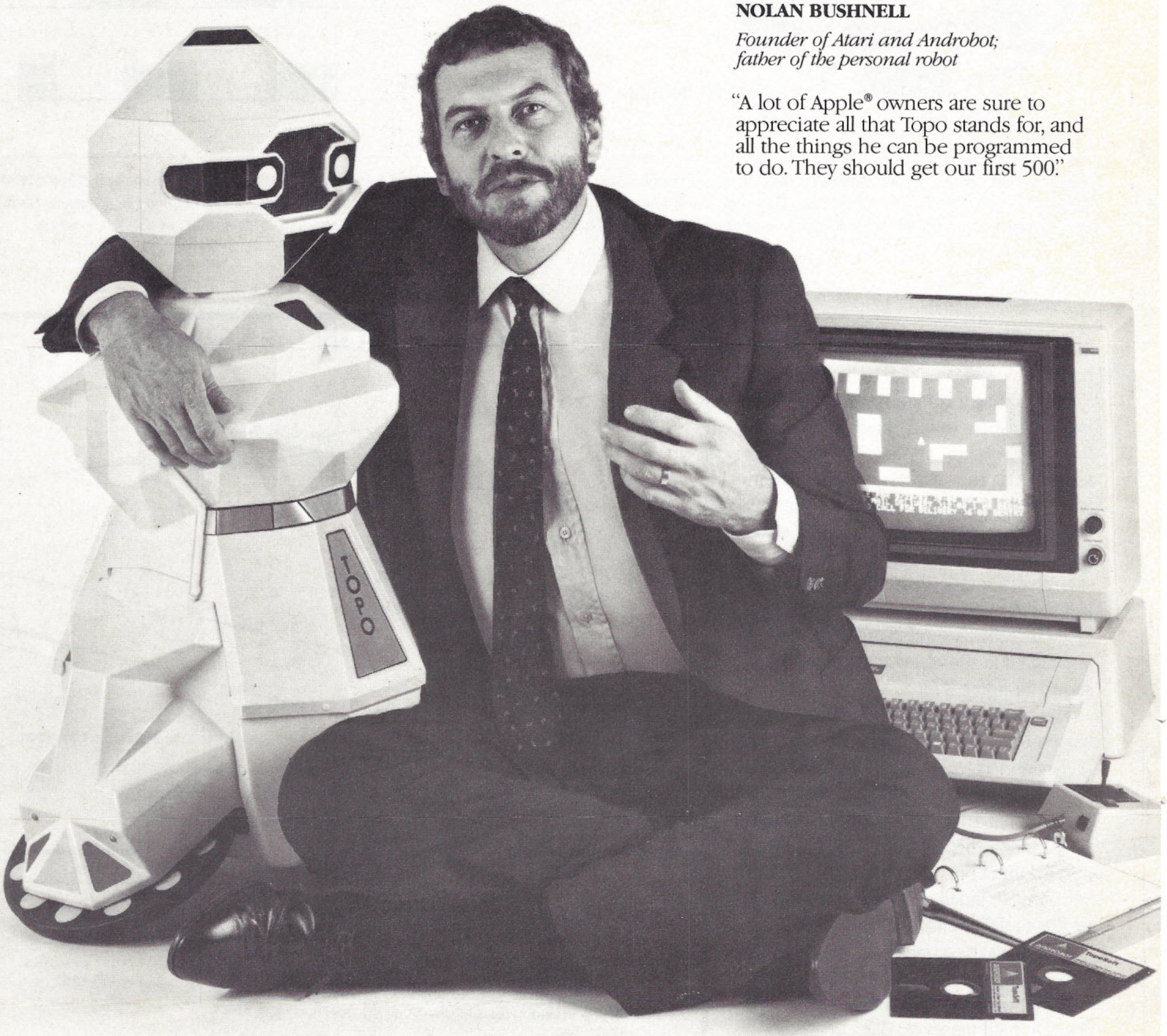

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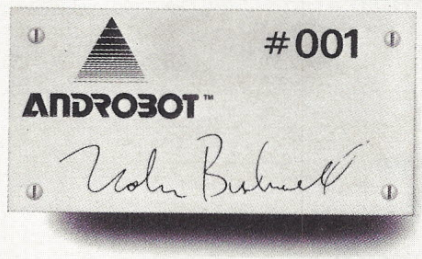

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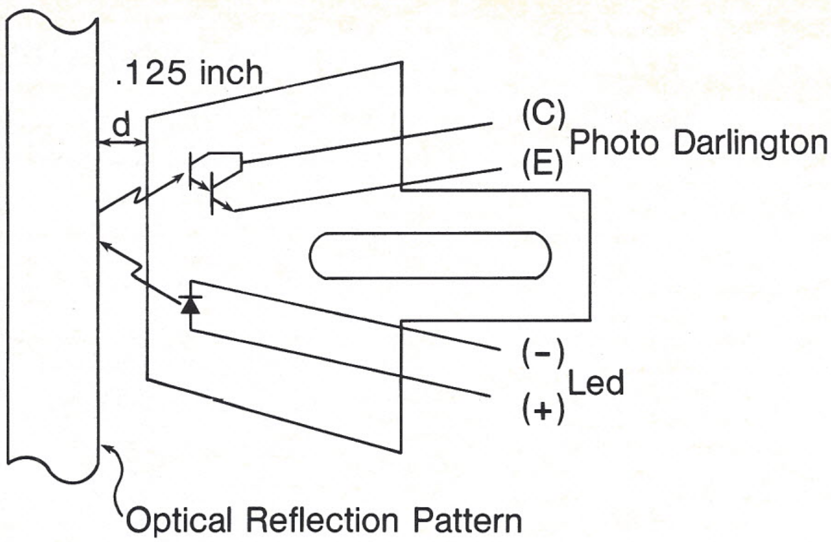

Figure 4. The optical sensor contains a light emitting diode (LED) and a phototransistor. A reflective surface causes the phototransistor to turn on, a light absorbing surface turns the phototransistor off. Shielding from external light sources is required to prevent 60 cycle interference.

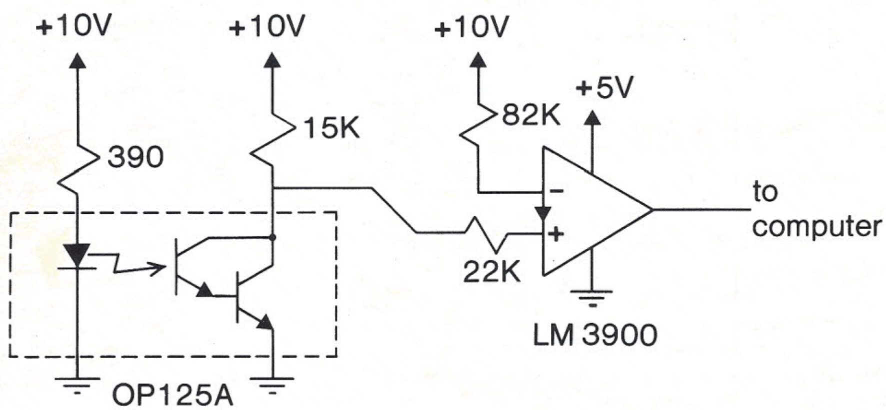

Figure 5. The photodarlington in the light sensor turns on when sufficient light is reflected from the LED. This brings the collector output to about 1V. Current flow into the negative input of the Norton amplifier is greater than the current flow in the positive input, resulting in a digital 0 output. When the LED is blocked, the photodarlington turns off, and the current flow into the positive input of the amplifier is greater than the negative input, causing the amplifier output to be a digital 1.

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solute position is maintained in the computer by starting at the mechanical stop and accumulating positive and negative increments.

Sensing Gripper Position. The gripper also lacks a simple rotation point on which a round magnet could be placed. In this case, however, we felt it was not important to know the gripper's precise position as long as we could determine if the gripper was open or closed. We accomplished this by gluing a small bar magnet to the side of the upper section of the gripper and mounting a Hall-effect sensor, as shown in photo 4.

Power Supplies. Super Armatron requires two power supplies: +12V and +10V. The 10V supply powers the Hall-effect transducers and must be very stable. The 12V supply actuates the solenoids and is regulated with series regulators to also provide +5V for the logic circuits and +3V for the motor. Capacitive filtering and ferrite beads are used on the motor leads to suppress noise.

Conclusion. Although this robot arm only lift can three ounces, it provides an accurate microcomputer-controlled robot for experimentation. The Pascal program we developed is only a starting point. Super Armatron is capable of performing much more complicated tasks, including direct and indirect kinematics, and moving multiple joints at the same time. More importantly, the techniques used to construct and program Super Armatron can be applied to larger industrial robots. □

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The November/December 1982 issue of Robotics Age *contained an article describing Armatron, a plastic robot toy from Tomy which is currently being sold by Radio Shack stores.*

The November/December 1982 issue proposed a contest for "a significant enhancement to the use and control of the system." Super Armatron by John Schiavone, Mike Dawson, and James E. Brandeberry of Wright State University is the contest winner. This team won due to its extensive feedback controls, simple software control language, and system documentation. Special mention goes to Lyn Mercer and Tony Beckett, also of Wright State University, who used the same robot as an automated typist.

About The Authors

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