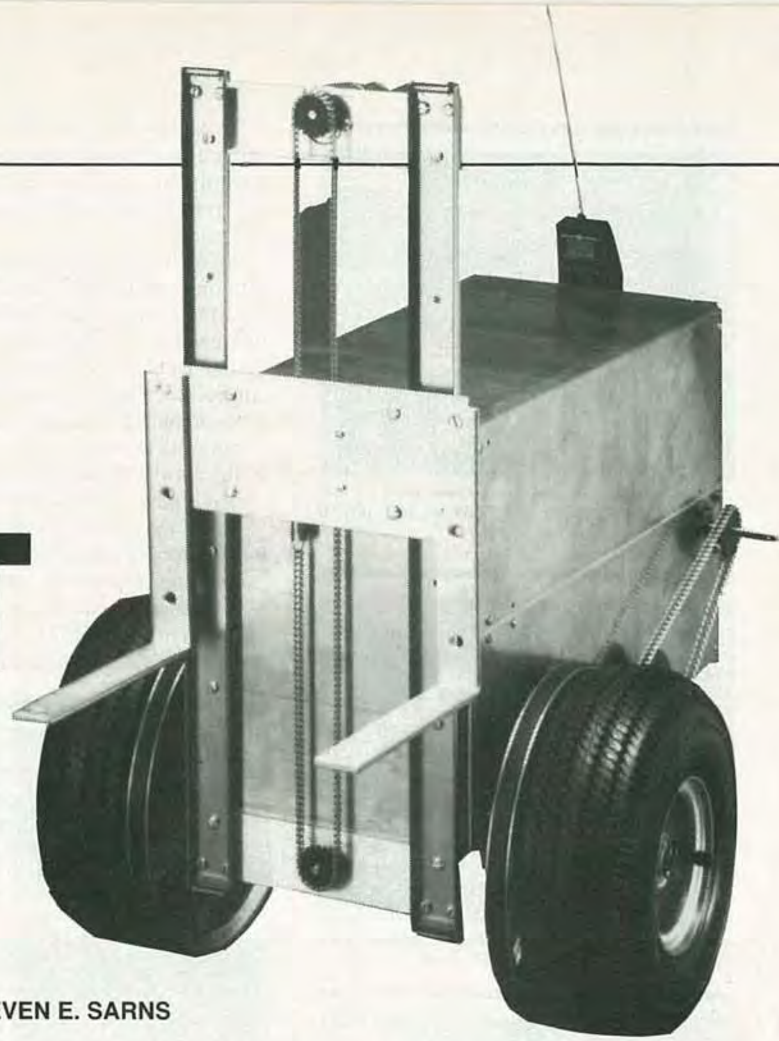
BUILD THIS

R-E ROBOT



Adding the arm, and the electronics to control it.

Part 11 IF YOU'VE BEEN FOLlowing this series, by now you have no doubt noticed that our robot does not have a traditional multi-jointed robotic arm. In its place is an "arm" that resembles a fork lift.

STEVEN E. SARNS

There are several reasons why that approach was chosen. First, it allows our robot to lift loads up to 10 pounds—multi-jointed arms usually are limited to lifting loads of one pound, or less. Second, our design is relatively inexpensive to implement. Third, few tasks actually require multi-jointed dexterity to get the job done—tasks performed with a multi-jointed arm often deteriorate into programming exercises. When we considered those factors, our design seemed to be the obvious way to go.

Of course, some tasks do require some measure of dexterity. For those, a pincher add-on for the lift has been designed; part of that pincher is shown in Fig. 1. The pincher will be described in detail in a future installment of this series. For now, let's concentrate on the basic fork-lift design.

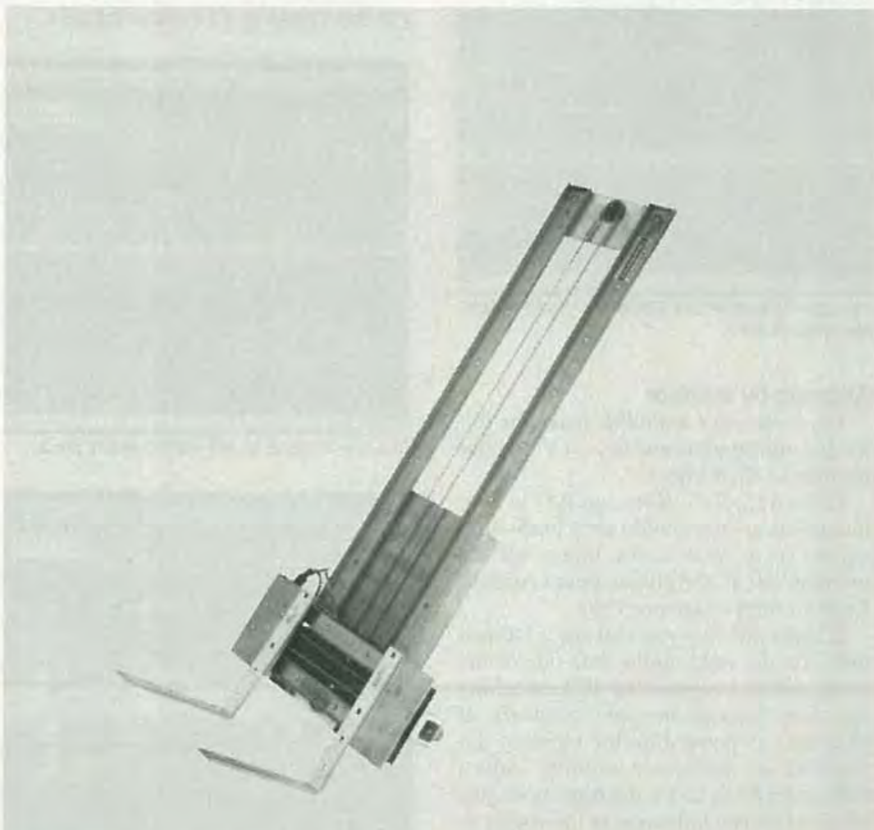


FIG. 1—THIS FORK-LIFT DESIGN can do almost as much as a multi-jointed arm, but with higher lifting capacity and at a lower cost. For greater dexterity, the pincher shown can be added. That pincher, part of which is shown here, will be described in detail in an upcoming installment of this series.

Mechanical overview

Our intention was to provide a rugged and reliable workhorse unit. The lift assembly has been designed to lift 10-pound loads from floor level to the top of a 32-inch-high table at a rate of 3 inches-per-second. The overall height of the assembly described is 43 inches. Exactly the same construction techniques can be used to build smaller (or larger) lifts.

Linear ball-bearing slides are used for the lift to preserve the efficiency of the system. Because of the way cantilever loads are coupled to the bearings, friction

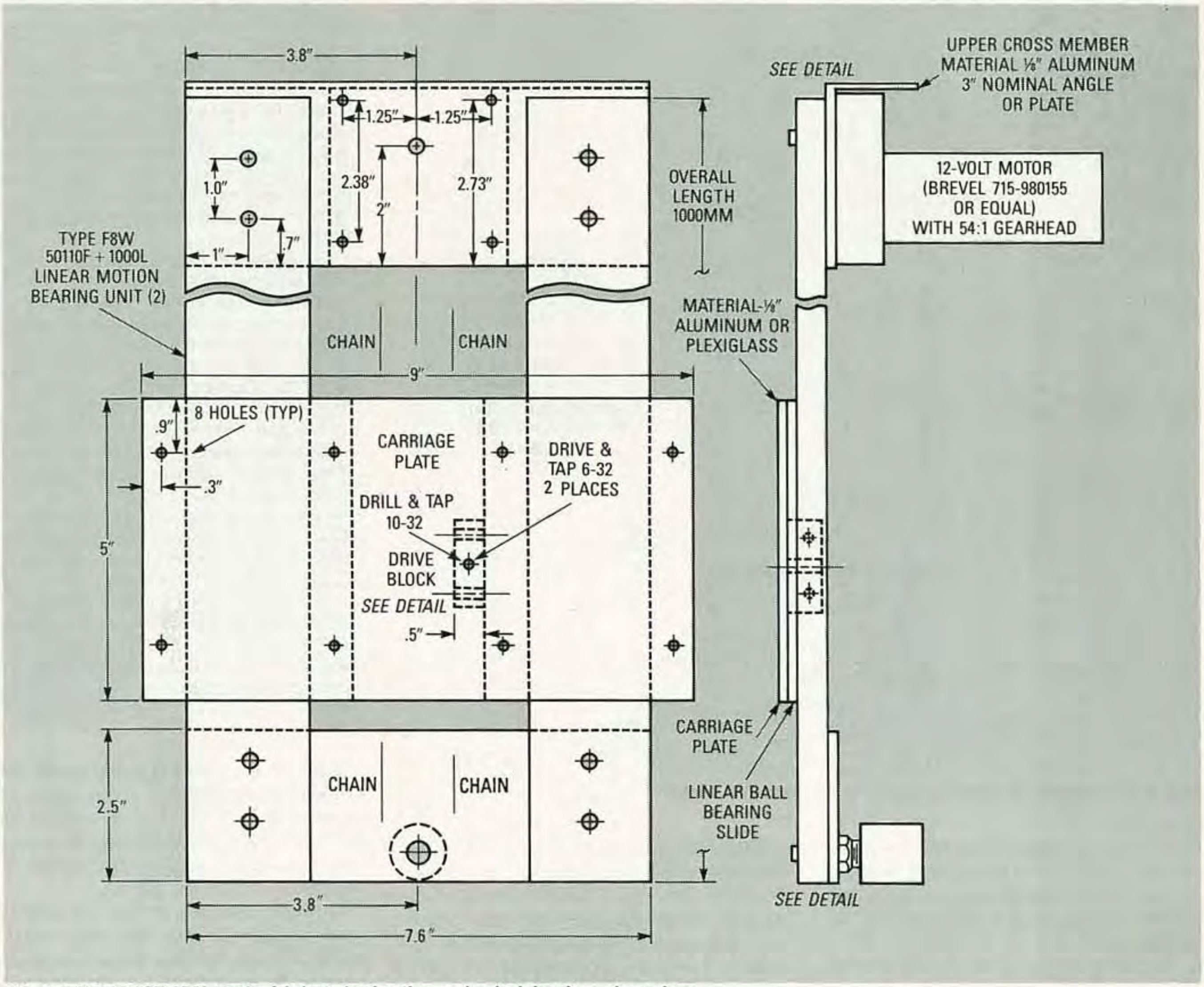


FIG. 2—THE ROBOT ARM can be fabricated using the mechanical drawings shown here.

could cause the required lifting force to become several times the total weight of the load on the lifting forks if sliding bearings were used. That would reduce the lifting capacity significantly. A chain drive is used to handle forces of 10 to 20 pounds without slipping and without any uncertainty about the lift position. The steel ladder-chain used is rated at 55 to 90 pounds tensile load. The drive motor is mounted at the top so that the lifting load is applied to its shaft and bearings directly (a ball-bearing version of that motor is desirable for heavy use). A potentiometer used for position-sensing is placed at the bottom of the chain loop as an idler; when it is mounted there, little load is placed on the potentiometer.

As with the rest of the robot project, the mechanical and electrical details cover our implementation of the arm. There are many other ways that the same results could be achieved. If you wish to change the design to accommodate a specific application, to incorporate an improvement, or to use components you have on hand, you may do so.

Note that much of the mechanical design of the arm can be credited to Spectron Engineering, and they provided the prototype on which this article is based. Further, Spectron is offering for sale the complete arm assembly. See the Sources box for more information.

Electronics overview

The electronics required to operate the arm are quite straightforward. We will use the robot's RERBUS expansion bus to communicate to a quasi-analog servo positioner. All the computer must do is to write the desired position of the arm to the servo circuit and that circuit will do the rest. The servo circuit also allows the computer to read back the position of the arm for analysis and direct control.

Arm design

The heart of the arm is the two linear ball-bearing slide units. Those are 1000-mm long, with approximately 35 inches of travel available. Our first task is to select the ladder chain-and-sprockets that move the carriage along those linear slides. We must select a sprocket for the potentiometer that will allow at least 35 inches of chain travel in ten turns of the sprocket, or 3.5 inches-per-turn. The ladder chain is ¼-inch pitch. Expressing 3.5 inches in terms of pitch length:

3.5 inches × 4 teeth/inch = 14 teeth (exactly)

In other words, if our potentiometer sprocket has 14 teeth, in 10 turns it will displace 35 inches of chain. We select the next larger sprocket, 15 teeth, resulting in a total chain travel of:

15 teeth × 0.25 inches/turn × 10 turns = 37.5 inches

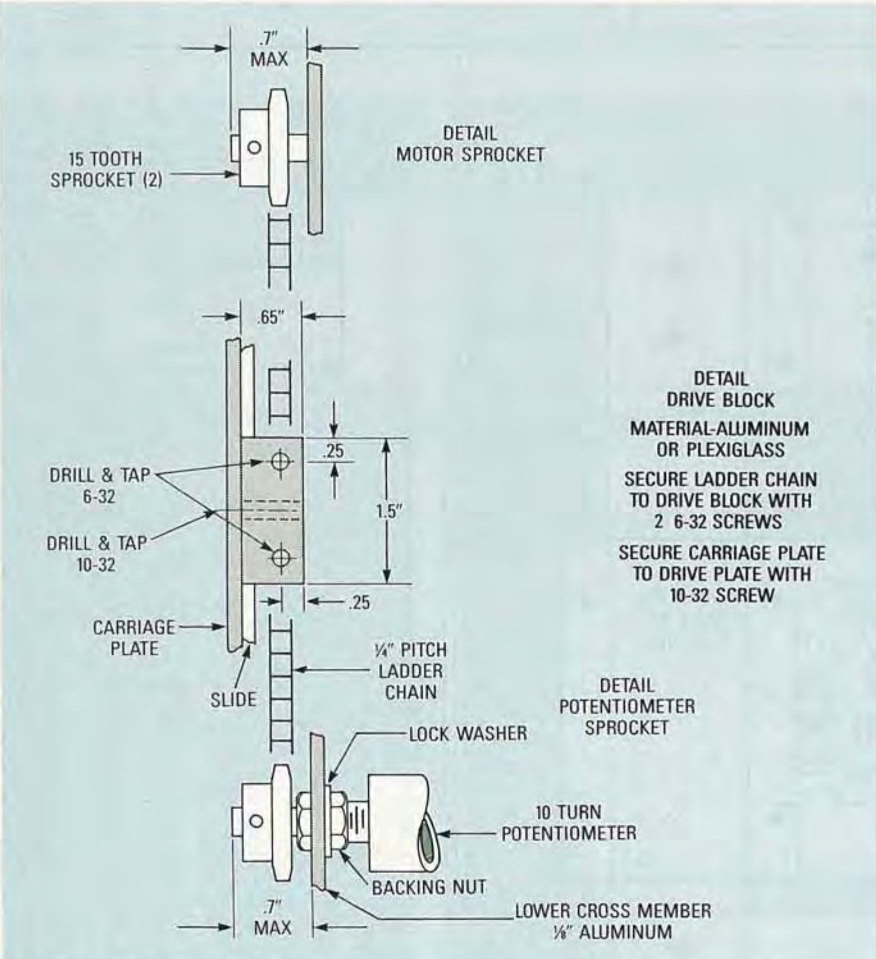


FIG. 3—THIS DETAIL DRAWING shows the ladder-chain drive system.

The extra 2 inches of chain travel will not be used and gives us a margin of error (± ¼ turn) in the event of some misalignment of the potentiometer sprocket during the assembly.

The motor used to drive the chain is any small DC motor with an attached gearhead. The motor may be rated from 12- to 36-volts DC. Using a motor rated at 12 volts will produce approximately twice the rated output, and using one rated at 36 volts will produce approximately ⅔ rated output. The only problem with using under-rated motors is heat build-up. Overheating should not be a problem if your applications call for a low duty cycle—the motor is never on for long, and is off most of the time. Assuming 3000 rpm and a 65:1 gearhead, the lifting speed will be:

(3000 rpm/60-sec/min)/65 = 0.77 rev/sec at sprocket

We can choose the lifting speed by selecting the sprocket size for the motor:

0.77 rev/sec × 10 teeth × 0.25 inch/tooth = 1.9 inch/sec

Other speeds can be calculated by plugging in the appropriate sprocket size. For instance, using a 15-tooth sprocket will give us a lifting speed of 0.77 × 15 × 0.25 = 2.9 inches-per-second, or 15 teeth × 0.25 inches/tooth = 3.75 inches-per-revolution.

Note that as you increase the lifting rate, the lifting capacity (in pounds) will be decreased. We have selected the 15-tooth design for more load capacity.

Turning our attention to the motor, the 15-tooth sprocket has a chain radius of approximately 0.5 inches. In order to lift 10 pounds, we will require a motor whose shaft can deliver a torque of 0.5 inches × 10 pounds = 5 pound inches.

We have chosen a Brevel 715-980155 gearhead 12-volt motor. The motor will be run at 24 volts, but that is not a problem because the motor will be subjected to a low duty cycle. The motor has a starting torque rating of 40 pound inches, which means that it can lift 40 pound inches/0.5 inches = 40 pounds. Its running torque is rated at 13 pound inches at 40 rpm, which means it can lift 26 pounds at a lifting speed of (40 rev/min/60 sec/min) × 3.75 inches/rev = 2.5 inches/second.

We can assume that the motor will deliver approximately twice the calculated performance if we run it at 24 volts. However, the servo circuit will limit the current drawn by the motor to approximately one ampere. That effectively limits the lift torque to about 10 pounds.

Arm construction

The arm can be built following the plans shown in Fig. 2; details for several sections of that drawing are shown in Fig. 3. The upper and lower cross-members can be made from aluminum plate, channel, or angle extrusion. Note that channel or angle form-factors are stronger than that of flat plate in resisting twisting

PARTS LIST

All resistors ¼ watt, 5%, unless otherwise noted
R1–R7, R9—100,000 ohms
R8—220 ohms
R10—47,000 ohms
R11—1 ohm, 1 watt
R12—10,000 ohms, 10-turn linear potentiometer
Semiconductors
IC1—DAC0832 digital-to-analog converter
IC2—74LS138 decoder
IC3—LM324 quad op-amp
IC4—UDN2952W motor driver
D1, D2—1N914 diode
Other components
J1—26-conductor ribbon-cable connector
TS1—5-position terminal strip
MOT1—12-volt motor with attached gearhead (see text)
Miscellaneous: Perforated construction board, wire, solder, mechanical components (see text), etc.

SOURCES

The complete arm assembly can be purchased from Spectron Engineering, 1342 West Cedar Ave., Denver, CO 80223; (303) 744-7088. The cost is $300 plus $8 shipping. Colorado residents add appropriate sales tax. The assembly includes the following: two 1000-mm linear-bearing assemblies, two cross members, carriage plate, robot end cover, drive block, chain, motor, sprockets, 10 turn potentiometer, servo positioner, cables, and connectors.

Stock Drive Products, Division of Designatronics, Inc. 2101 Jericho Turnpike, New Hyde Park, NY 11040, (516) 328-0200, can supply the 15-tooth ¼-inch pitch sprocket (part number 6T7-2515) and the ¼-inch ladder cabin (part number 6C88-25). Contact them directly for pricing, shipping, or other information.

The 1000-mm linear ball-bearing slides are manufactured in Japan by T.H.K. Ltd. They can be purchased from Bearing Engineers, Inc., 6009 Bandini Blvd., Los Angeles, CA 90040; (213) 754-9660. Contact them directly for pricing, shipping, and other information. Ask for part number FBW 50110F+1000L.

The Brevel motor, part 715-980155, can be purchased from Johnstone Supply, 930 Wyandot, P.O.Box 4605, Denver CO 80204; (303) 573-5626. Contact them for pricing and shipping. **R-E**

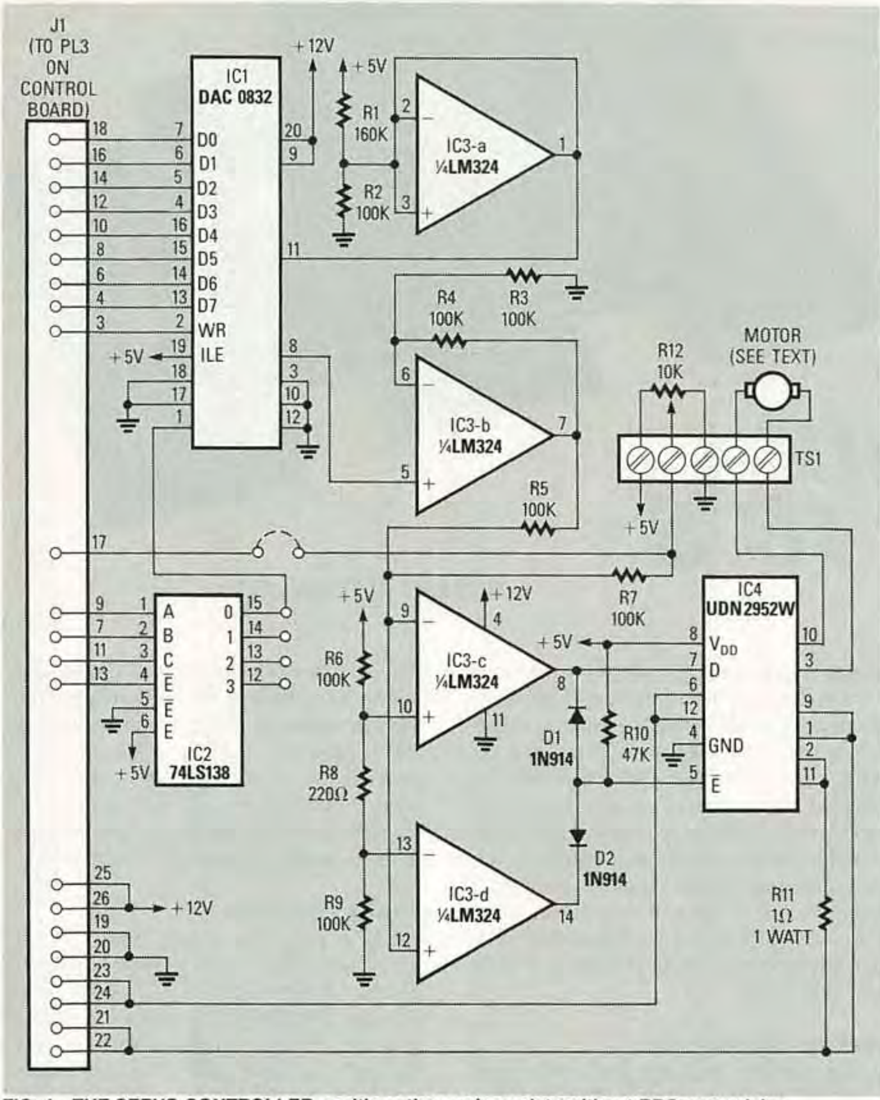


FIG. 4—THE SERVO CONTROLLER positions the carriage plate without RPC supervision.

forces imposed by off-center loads and provide additional mounting surfaces for future projects. Mount the motor on the upper cross-member so that the shaft is offset to the top, and secure it to the face of the cross-member using 10-32 flat head screws. The potentiometer should be mounted at the bottom of the lower cross-member. When mounting, use double nuts or extra washers so that the mounting bushing extends only 1/16-inch beyond the mounting nut. Installing the motor and potentiometer as described will allow for the maximum possible travel of the linear bearings with a minimum overhang of the cross-members.

The cross-members are mounted to the back of the linear bearing tracks. Those tracks are part of the 1000-mm linear bearing assemblies, which can be purchased from the company mentioned in the Sources box; they are also provided with the complete arm assembly that was mentioned previously.

Next, mount the carriage plate to the front of the sliders with 10-32 screws. The carriage plate should slide over the entire length of the tracks and overlap the motor mount in the end position. If the carriage plate jams, correct the problem by readjusting the mounting screws. Note that the type of slide bearings used in this assembly may bind somewhat, particularly when unloaded. But under load, the bearings provide low friction and long operating life.

The sprockets should now be mounted on the motor and potentiometer. They are positioned with the hub outward so that the working load is kept close to the bearings. The set screws on the sprockets have a bad habit of working loose, so seal them after installation with nail polish, *Loctite*, etc.

Check to be sure that the carriage clears the sprockets and shafts of the motor and potentiometer. Install washers behind the carriage plate to move it away from the sprockets if you have an interference problem. In some instances, you may have to saw off the ends of the motor and potentiometer shafts to achieve clearance.

Next, turn the potentiometer fully clockwise. Use a piece of tape to hold it in that position until the chain installation is complete. Note that if the potentiometer is not positioned properly the full carriage travel will not be available; or worse, the potentiometer stops can be damaged if the full power of the motor is applied to them. Thread the chain over the motor and potentiometer sprockets, open it, remove enough links so that it is the correct length, and reassemble the chain. Move the carriage all the way to the top of the assembly and attach it to the chain via the drive block. Be sure to thread the chain so that it is inside the block; i.e., closer to the centerline.

An alternate to closing the chain into an endless loop is to connect the ends using a spring. Doing so serves to eliminate backlash from chain slack and lessens the load on the potentiometer. However, under heavy loads, the spring may allow the chain to become slack, allowing slippage at the sprockets. Although usually that is not a problem, slippage can be eliminated entirely by not using a spring.

The lifting tines of the fork lift are formed using 8- to 10-inch steel L-brackets. You will probably need to drill some extra holes to allow you to mount the bracket to the carriage plate. If you wish, you can add the holes in such a way to allow the brackets to extend below the slide bearings and reach the floor. Mount the tines to either the outer or inner row of carriage-plate holes to accommodate the width of your anticipated loads.

Attach a 26-conductor ribbon cable to the RERBUS interface on the control board, and lead the cable out through the bottom of the robot's body. Finish up by mounting the arm assembly on the robot's end cover using four 6-32 screws. In our implementation, we split that end cover into two sections to allow for easy access to the fastening nuts and the electronics package, which is mounted on the forward bulkhead.

Arm electronics

The control system for the arm is straightforward. Once notified of the final position for the carriage plate, the system will move the plate to that position without further attention from the *R*obotic *P*ersonal *C*omputer (RPC).

A schematic of the control system is shown in Fig. 4. After determining where the carriage plate should be positioned, the RPC writes a position value into the *D*igital-to-*A*nalog *C*onverter (DAC). The quasi-analog servo system takes over and begins slewing the motor toward the selected position. When the voltage fed back from the potentiometer is equal to the voltage output from the DAC, the system knows that the selected position has been reached and the motor is turned off. All during that time the computer is free to begin analyzing the next required motion.

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Even if the motor encounters resistance, it will continue to move in the necessary direction until the voltage outputs from the potentiometer and the DAC are equal. Later on, if the carriage plate encounters enough resistance to move it away from the selected position, in either position, the drive circuit will return the carriage plate to the selected position as soon as it is able to, without further action by the computer.

The circuit we used to accomplish all that is surprisingly simple. As shown in Fig. 4, a DAC0832 DAC configured in the voltage mode is used to output the desired analog position. One section of an LM324 quad op-amp buffers the output of the DAC, while another multiples a 2.5-volt reference voltage by two, resulting in a 0- to 5-volt output range. Two other sections of the LM324 are used to compare the output of the DAC to the output of the position-sensing potentiometer; the output of the potentiometer corresponds to the actual position of the carriage plate. When the voltage from the potentiometer is exactly equal to the output from the DAC, but *opposite* in sign, with respect to the 2.5-volt reference, the circuit shuts down the motor. A small dead band is introduced into the comparator circuit to insure that the motor is not forced to oscillate about its target position. A single 74LS138 address decoder is used to enable and disable the circuit.

The entire control circuit, minus of course, the potentiometer and the motor, can be mounted on a small (2 × 2.5 inches) piece of perforated construction board; the layout is not critical. When finished, the circuit board can be mounted near the potentiometer using double-sided foam tape or standoffs.

Software

Note that the use of a 15-tooth sprocket results in more chain travel in 10 turns of the potentiometer than the linear ball-bearing slide can achieve. That means that it is possible to program positions that are beyond the travel limits of the carriage plate. If that is done, the motor will continue to turn after the ball-bearing slide has hit a stop. Therefore, the values for the limits of travel must be determined experimentally, and the software set up to disallow values greater than those limits.

The RERBUS interface that is used to communicate with the arm electronics is controlled by two digital ports so that all timing problems vanish. We must write the data to one port and use the other port to set up our address and control signal. We will create two Forth words to do that: XPC@ and XPC!

```
:XPC@ (address — data)
   DUP ( save copy of address )
   80 OR ( set WRITE high )
   BF AND ( set READ low - active )
   130 PC@ ( get the data from 130 )
   SWAP ( get the old address )
   C0 OR 140 PC! ; ( both strobes high )
:XPC! (data address —)
   SWAP 130 PC! ( write data to port )
   DUP ( save a copy of addr )
   40 OR ( set READ strobe high )
   7F AND ( set WRITE strobe low )
   140 PC! ( write addr and cntrl )
   C0 AND 140 PC! ; ( both strobes
   high )
```

Those two words are direct analogies of the Forth words PC@ and PC!, which fetch and store bytes to ordinary ports.

Notes

The mechanical aspects of the arm are easily modified to suit your needs. If you wish to do so, here are some design factors to keep in mind. When considering whether to increase the arm's lifting capacity, remember that the capacity must be consistent with the design of the robot. It's pointless to design an arm that lifts 100 pounds with ease if lifting such a weight will cause the robot to topple forward.

The steel ladder chain is rated at 90 pounds yield strength. Allowing for a 50% safety factor (highly recommended) means that you can use the ladder chain to lift to about 45 pounds. If your requirements call for loads that are greater than that, you will have to use a different style of chain (for example, riveted ¼-inch roller chain).

The motor and gearhead are the governing factors for lifting capacity and speed. The lift motor should draw no more than 3 amps, the rating of the connecting ribbon cable. Use of a worm-gear style gearhead would improve the design because then the load could not back drive the motor.

The orientation of the linear ball-bearing slides deserves some consideration. Building the lift assembly is easiest when the slides are oriented as described in this article. However, greater loading capacity would be achieved if the slides were mounted on aluminum angle and rotated 90°. That would allow the use of less costly FBW3590NF series linear bearings instead of the FBW50110F series specified. While the FBW3590NF series is only available in 800-mm maximum lengths, several sections could be joined together to yield any overall length desired.

The Brevel motor specified comes with mounting holes for a shaft encoder. That means that we could use the same position sensing scheme as the main motor (shaft encoder and quadrature decoding). That would allow for greater accuracy when positioning the carriage plate. See Part 7 in the July 1987 issue of **Radio-Electronics** for more information. **R-E**