

Inside RTX

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Before you begin

This is one of a set of five guides to the basic RTX. It gives information about RTX's design, mechanics and electronics.

Introducing RTX explains how to set up the arm, test it, and run some demonstration software. You should read it before looking at any of the other guides.

Programming RTX using the library describes the library of routines that have been provided with the arm, and contains an example of how to implement them using Turbo Pascal.

Using Intelligent Peripherals Communications describes the protocol which UMI have developed for controlling RTX. You should read it if you want to control the arm directly with the Intelligent Peripherals Communications protocol, and by-pass the library of routines described in *Programming RTX using the library*.

Forth Teach and Replay explains how to program the arm quickly and easily. It introduces the Forth control language.

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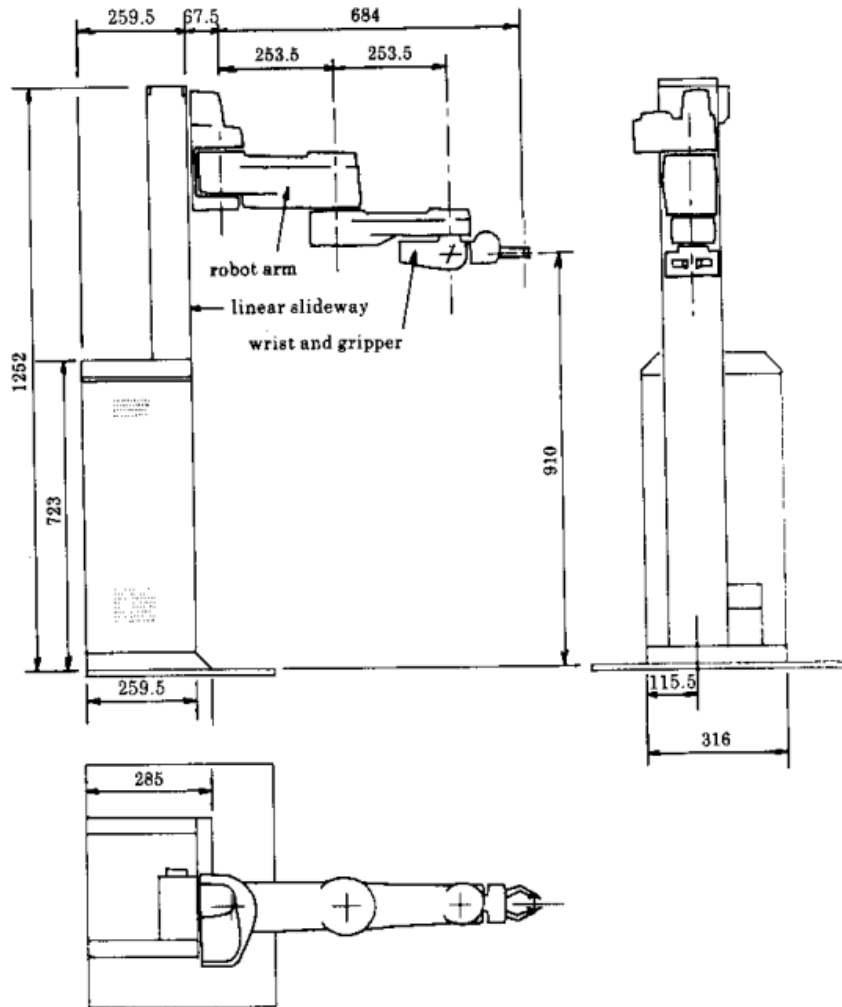
About this guide

This guide gives a description of RTX's design, mechanics and electronics. It is aimed at all RTX users who need to know more about the principles behind the robot arm.

The guide assumes some familiarity with RTX, and a basic knowledge of engineering design and motor control systems.

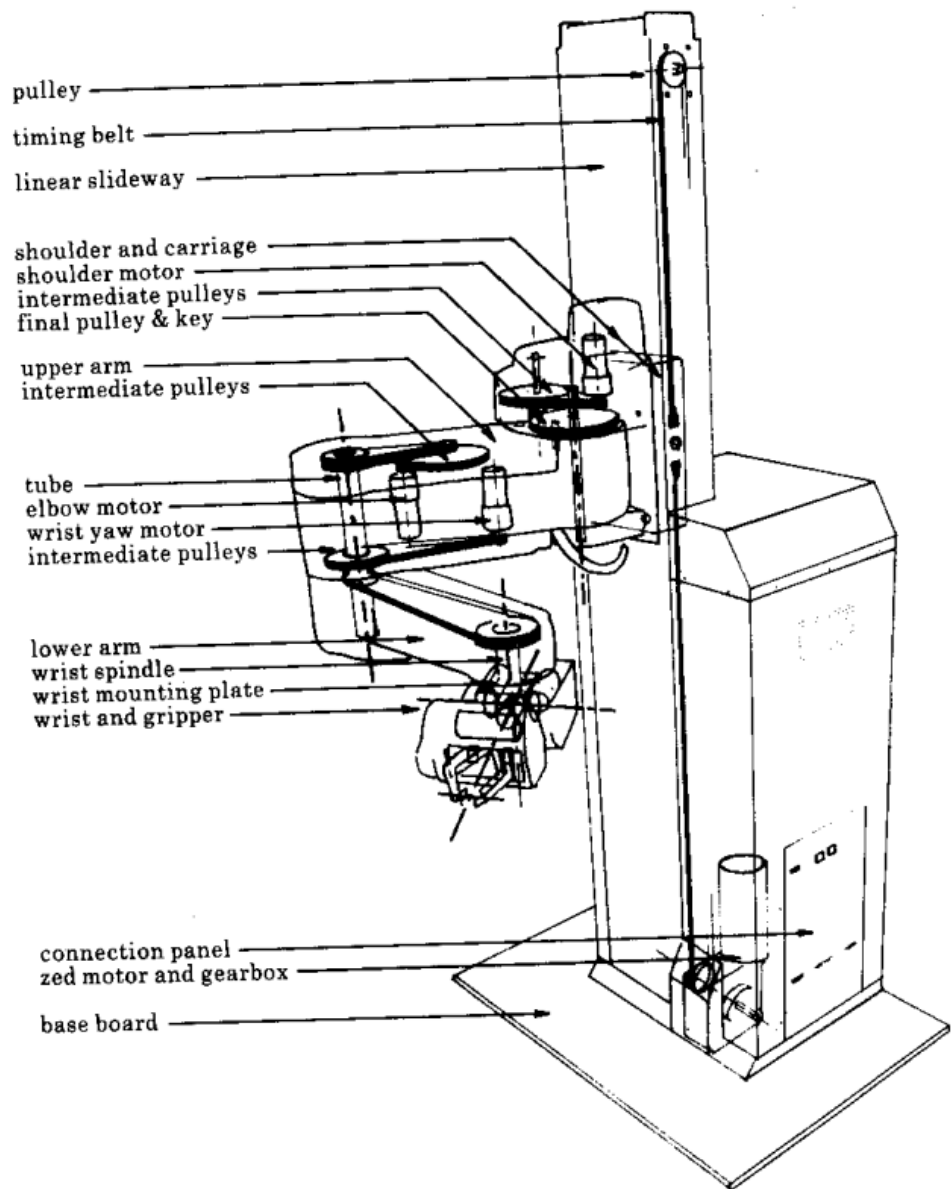
Design information

This diagram shows the dimensions of RTX.



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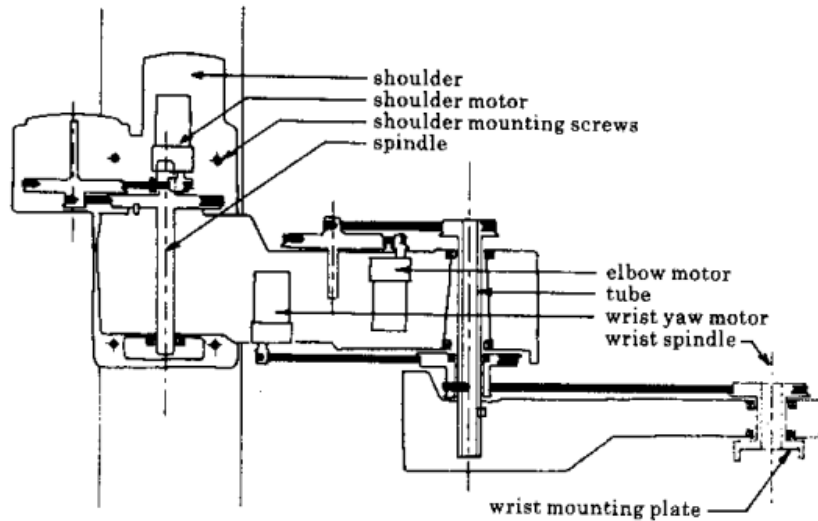
The overall weight of the arm is 35 kg, 77 lb.



This diagram shows the whole robot assembly. The shoulder casting is fitted to RTX's linear slideway by four socket-head screws. The shoulder holds a vertical spindle which lets the upper arm swing in a horizontal plane on its bearings.

The lower arm is fixed to a tube that rotates in bearings in the upper arm, allowing it to swing in a horizontal plane.

The robot arm



The upper arm is driven by the shoulder motor through a gearbox and a two-stage belt reduction. The final pulley is fixed to the upper arm. The intermediate combined pulley is on an eccentric spindle that allows the secondary belt tension to be adjusted. The shoulder motor is on a slotted plate to allow the primary belt tension to be adjusted.

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The elbow motor, which drives the lower arm, works in a similar way using a gearbox and two-stage belt reduction. The elbow has similar belt adjustment to the shoulder.

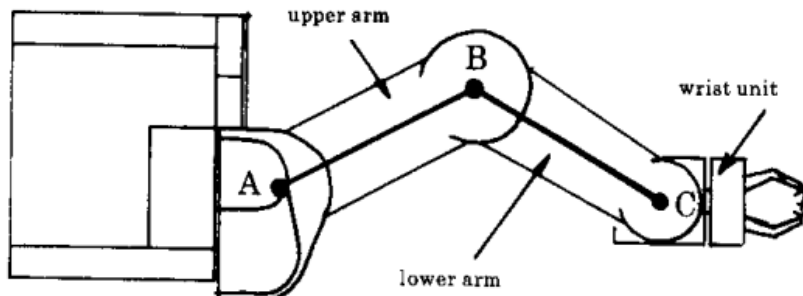
At the end of the lower arm, there's a plate to which the wrist unit is normally fixed -- though you can fit other kinds of end effector if you prefer. This wrist mounting plate is driven by a third motor -- the wrist yaw motor located in the upper arm -- again through a gearbox and a series of pulleys.

The lower arm can stow underneath the upper arm. As supplied the arm is configured as a left-handed arm.

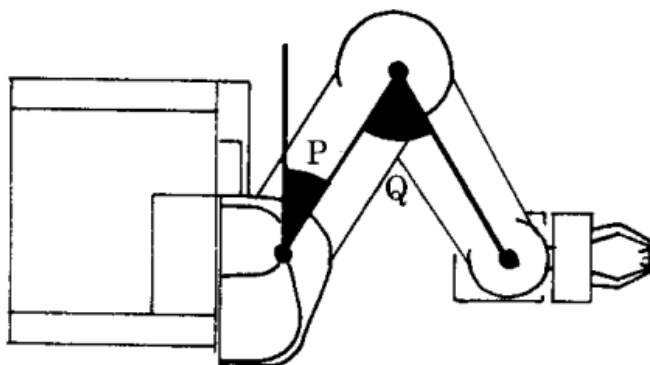


The geometry of the arm

The upper arm and lower arm are the same length: AB equals BC .

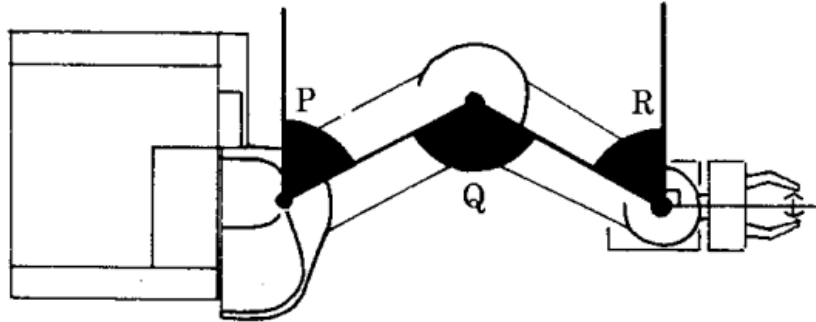


This means that you can move the wrist in a straight line outwards from the column -- a radial line between the shoulder and wrist spindles -- by rotating the two parts of the arm, making sure that angle P is always half angle Q :



The gear ratio from the shoulder motor to the upper arm is twice that of the elbow motor to the lower arm. To move the wrist in a radial line, you therefore drive the two motors at the same speed but in opposite directions. The benefit of this arrangement is that you can keep track of the wrist's position in cylindrical co-ordinates very easily, by simple calculations based on the motor encoder counts. (Encoder counts are the units in which the movement of an RTX motor is measured.)

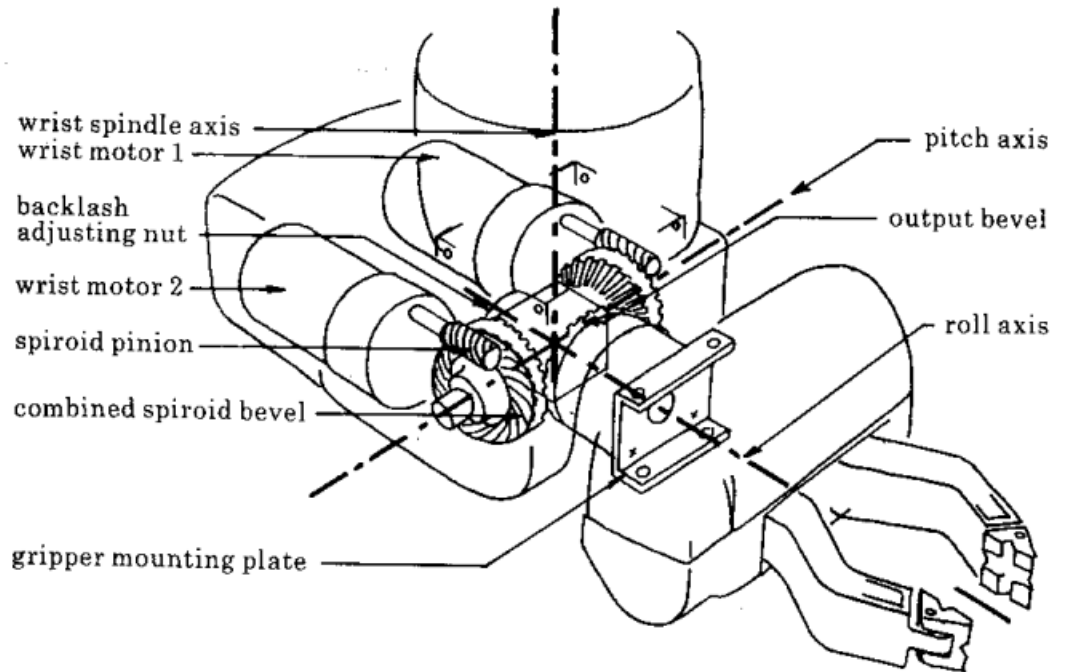
In addition, you can keep the gripper pointing along the radial line by keeping angle R the same as angle P:



This is achieved automatically without needing to drive the yaw motor. When the lower arm moves through an angle Q , the wrist automatically moves through R , which is $Q/2$, because of the 2:1 gear ratio from the combined pulley which rotates on the elbow spindle and the wrist pulley.

Because of this automatic compensation, it's possible with certain yaw orientations for the wrist to hit its end stops when driving the arm radially in and out. This is to be avoided as it causes the belts to jump, giving a ratchet sound: it could cause damage if done repeatedly. If this happens, the arm will lose position and will need to be re-initialised.

The wrist and gripper



The wrist unit is fixed by four screws to the lower arm's wrist plate. This means that the wrist unit can be taken off, and some other piece of equipment attached. The unit contains two geared motors, called wrist 1 and wrist 2. Each drives a spiroid pinion and a combined spiroid bevel gear, which in turn drives an output bevel gear. The backlash in the wrist is controlled by a castellated adjusting nut. This controls the backlash in both the bevel gears and the spiroid pinions.

action you want	how to drive the two motors
pitch	at the same speed in the same direction
roll	at the same speed in opposite directions
both pitch and roll	at different speeds

table 1

Pitch in degrees is given by:

$$\left(\frac{w1 + w2 * k}{2} \right)$$

and roll in degrees is given by:

$$\left(\frac{w1 - w2 * k}{2} \right)$$

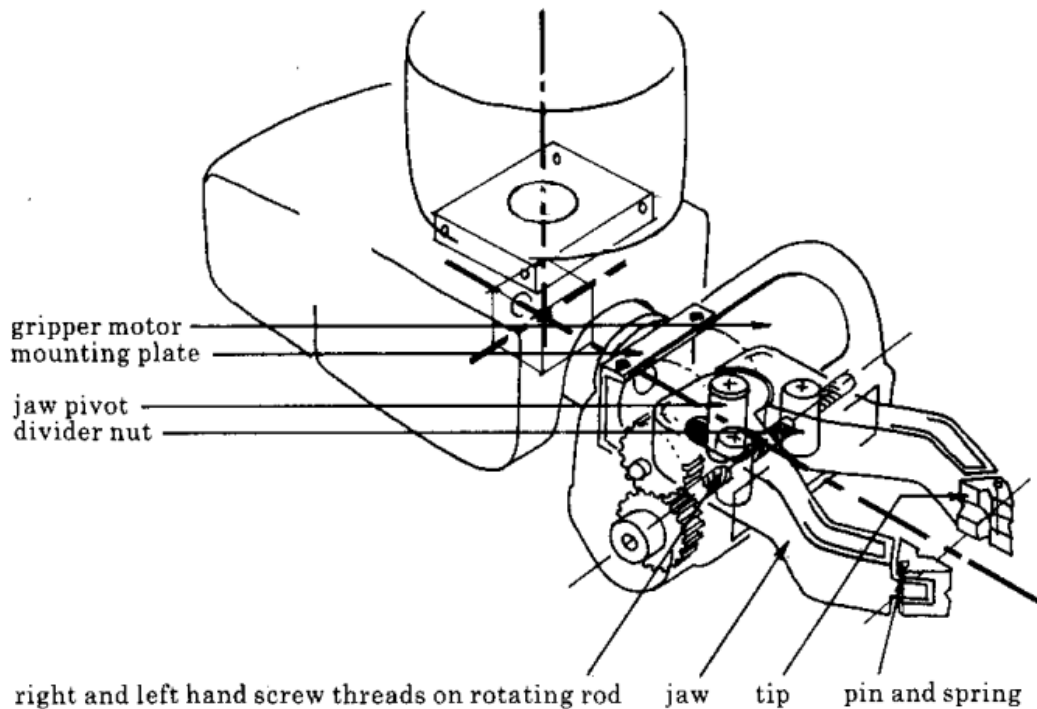
where:

- ... w1 is encoder counts for wrist motor 1
- ... w2 is encoder counts for wrist motor 2
- ... k is the scale factor to convert counts to degrees (k = 0.07415).

The gripper

The gripper is fixed to the wrist unit by two screws, through a removable plate. This makes it easy to fix a different gripper or end-effector to the wrist.

The gripper consists of two identical moulded jaws, each linked to a tip. The tip is free to rotate about a pin, and is kept in an open position by a spring.



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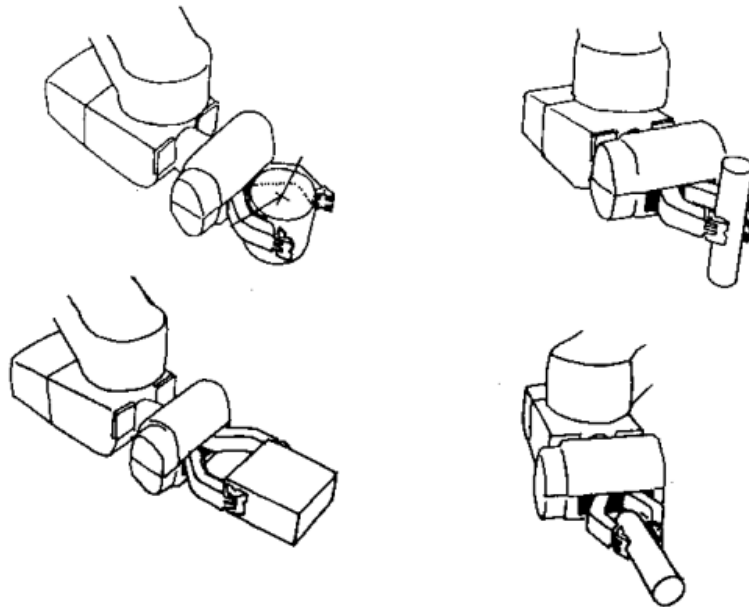
The jaws are moved by a threaded rod with right-and-left-hand screw threads. This rod is driven from a geared motor by spur gears. Rotating the rod in one direction opens the jaws; rotating it the other direction closes them. The jaw pivot pin extends into a slot in the housing and keeps the jaws central.

The gripper has full servo control allowing position, speed and force to be controlled.



How the gripper holds objects

The gripper is designed to be able to hold a range of differently-shaped objects.



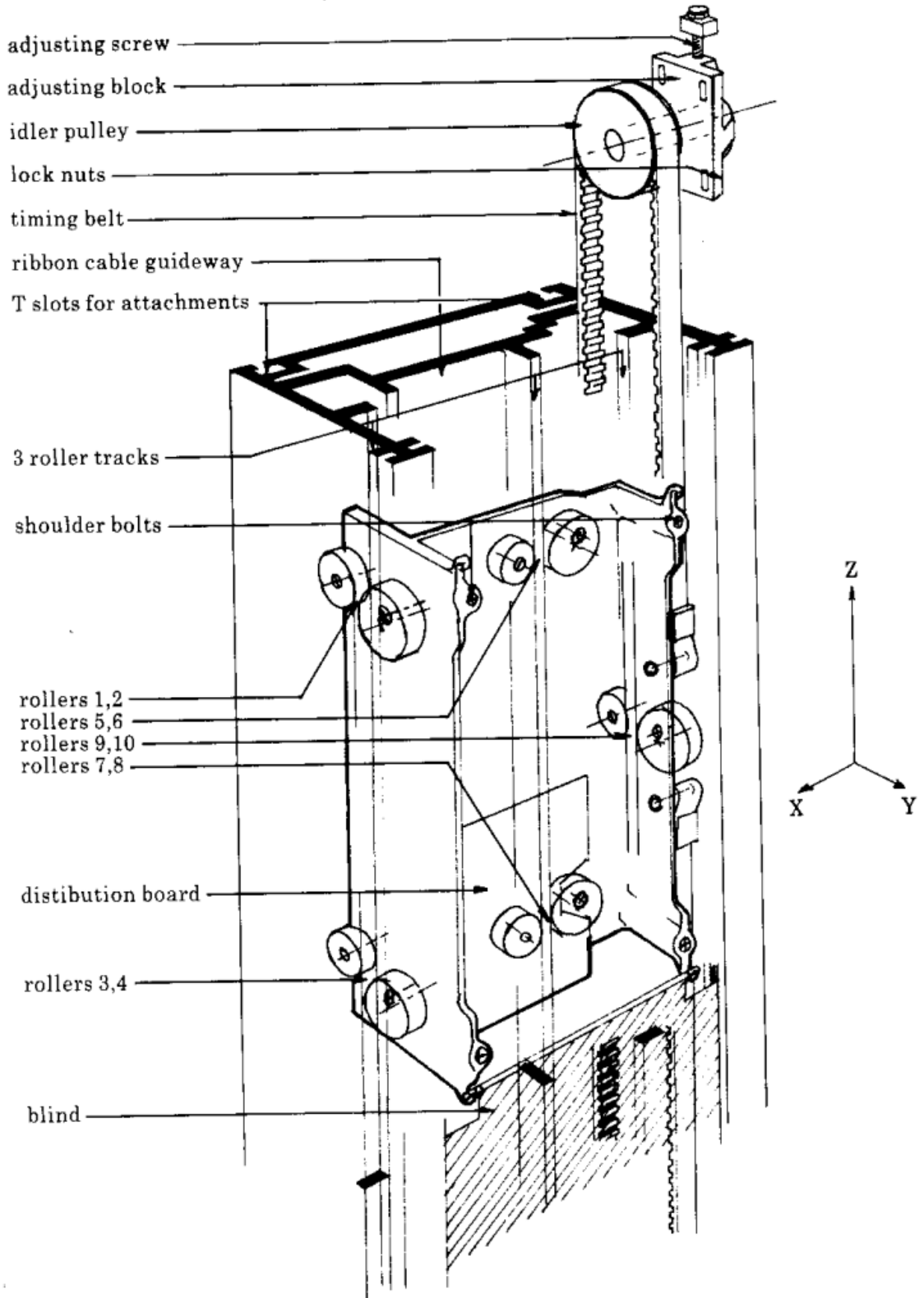
The linear slideway

The slideway consists of:

- ... a column of extruded aluminium
- ... a carriage which is driven up and down the column by the zed motor through a pulley and a timing belt; the carriage has ten rollers, five of which are on adjustable eccentrics
- ... a ribbon cable taking data and power to a distribution board on the carriage
- ... a blind which covers and protects the cable
- ... an idler pulley at the top of the column, with an adjusting block which allows the zed-axis belt tension to be adjusted
- ... the zed motor with a 25:1 worm gear box drive pulley, an encoder and a one-way friction brake assembly.

The brake assembly allows the arm to be driven up the column unimpeded, but applies a friction force to compensate for the weight of the arm as it descends.

In cross-section, the column looks like this:



- Each of the five pairs of rollers consists of:
- ... a precision bearing with a plastic tyre on a concentric spindle
 - ... a larger bearing with a plastic tyre on an eccentric spindle.

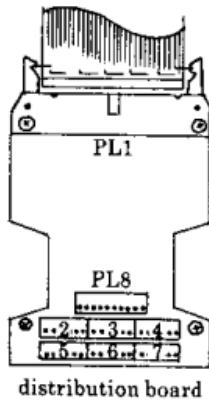
The eccentric spindles allow play to be adjusted out of the slideway.

rollers:	run along track:	and control bending forces in:
(1,2), (3,4)	a	the YZ plane
(5,6), (7,8)	b	the XZ plane
(9,10)	c	the XY plane

table 2

The distribution board

The distribution board takes power and signal wires from the carriage to the arm motors and the ancillary socket in the arm assembly. The number of pins in each connector and the part of the arm that it links to is shown below.



connector number	number of pins	links to
1	40	
2	6	ribbon cable
3	6	wrist 1
4	6	wrist 2
5	6	yaw
6	6	shoulder
7	6	elbow
8	10	gripper ancillary

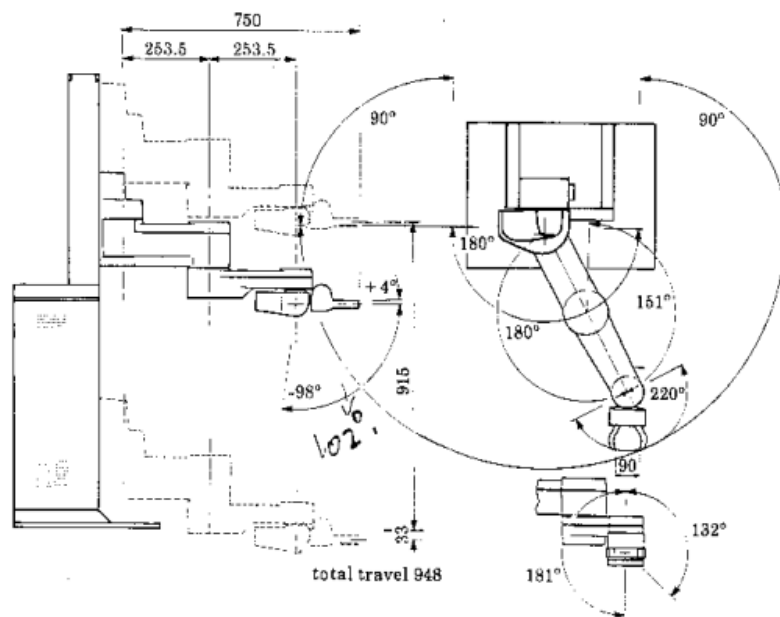
table 3

How the arm is driven

RTX is driven by seven precision 24 V DC motors. One motor with 20 W output power controls the vertical motion. Six others of 3 W output power control the other axes. Each motor is fitted with a two-phase optical incremental encoder, so that the software can monitor how far the motor has moved, and in what direction.

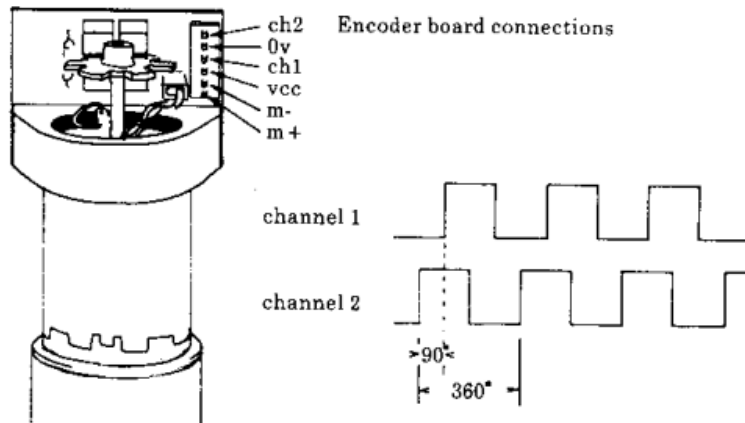
Range of movement

RTX's range of movement is shown in this diagram.



The encoders

Each encoder consists of a small printed circuit board, attached to the motor, and a moulded plastic disc pressed on the extended motor spindle. The disc has vanes which pass between the two slotted opto-switches mounted on the pcb. Each of the switches generates a square wave arranged to be 90 degrees out of phase to the other, as shown in the diagram.



This is known as a quadrature output. Both the direction and the position of the motor can be determined from the two-phase signal.

Channel 1	high	high	low	low	high	high	low	low
Channel 2	high	low	low	high	high	low	low	high
		A<		>B				

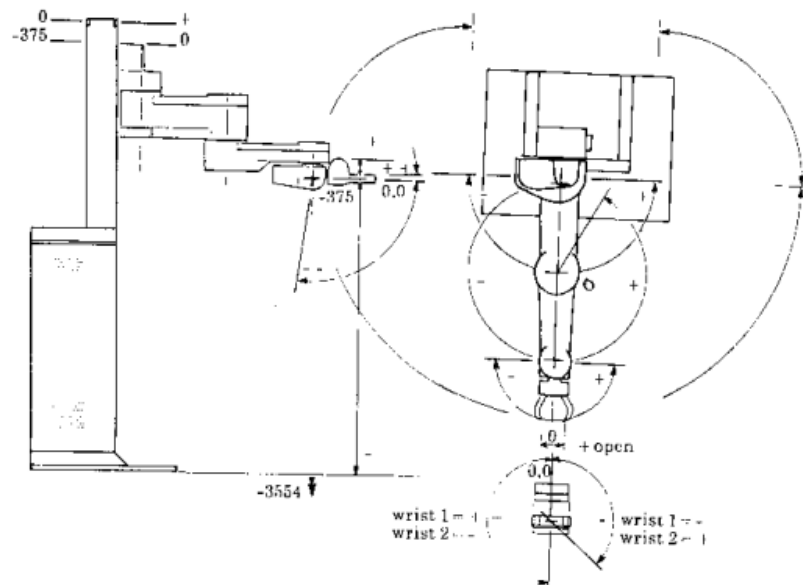
If both channels are low, then:

- if channel 2 goes high, the motor is moving in direction B
- if channel 1 goes high, the motor is moving in direction A.

This quadrature signal means that the positional resolution can be four times greater than the number of vanes on the disc. In practice, the RTX firmware counts only two of these state changes giving 12 counts per motor revolution for the six-vane disc on the small motors and 24 counts per motor on revolution for the 12-slot disc on the zed axis motor.

Initialised position and direction of movement

When the arm is initialised, it should be in this position:



The arrows in the diagrams show positive movements.

When both wrist motors are moving in the positive direction, the gripper pitches upwards. When the wrist 1 motor is moving in the positive direction and the wrist 2 motor is moving in the negative direction, the gripper rolls clockwise when viewed from the shoulder.

When the arm is in the initialised position, the encoder counts are as follows.

zed	-375
shoulder	0
elbow	0
wrist yaw	0
wrist 1	0
wrist 2	0
gripper	0

table 4

When the arm is at the top of the column, the encoder counts for zed are 0.

The ranges of travel for the arm axes, from the initialised position are as follows:

axis	endstop to endstop encoder counts	total range mm or degrees	encoder counts
zed	0 to -3554	948 mm	3554
zed	underside of wrist to baseboard	881 mm	3303
zed	gripper pointing downwards to baseboard	738 mm	2767
shoulder	+2630 to -2630	180 degrees	5260
elbow	+2206 to -2630	331 degrees	4836
yaw	+1071 + e/3 to -1071 + e/3	220 degrees	2142
pitch	w1 + w2 = 108 to -2642	102 degrees	2750
roll	w1 - w2 = 4882 to -3560	313 degrees	8442
gripper	+1200 to -30	90 mm	1200

table 5

In the table:

- w1 is the encoder count for wrist 1
- w2 is the encoder count for wrist 2
- e is the encoder count for the elbow motor.

The values are calculated and may vary from machine to machine.

Motor gearing

An encoder count corresponds to a different angle or distance for each motor, depending on how it is geared. All the motors except zed have the same first stage gear reduction of 20.23:1 followed by belt and pulley or spiroid/bevel reduction to give:

motor	number of counts per motor revolution	gear ratio	movement per encoder count
zed	24	25:1	0.2667 mm
shoulder	12	876.633:1	0.03422 degrees
elbow	12	438.317:1	0.06844 degrees
yaw	12	292.211:1	0.10267 degrees
wrist 1	12	404.6:1	0.07415 degrees
wrist 2	12	404.6:1	0.07415 degrees
gripper	12	20.23:1	see below

table 6

The next table shows the number of encoder counts needed to produce a specified movement.

motor	movement	encoder counts
zed	1 mm	3.74953
shoulder	1 degree	29.2227
elbow	1 degree	14.6113
yaw	1 degree	9.73994
wrist 1	1 degree	13.4862
wrist 2	1 degree	13.4862
gripper	1 mm	see below

table 7

The gripper motor has a right-and-left-handed ACME thread, pitch 16 tpi (threads per inch). The relationship between the rotation of the gripper motor and the separation of the two halves of the gripper isn't linear. A good approximation is:

$$\text{separation in mm} = (0.0584 * c) + (10.7 * 10^{-6} * c^2)$$

where c is the number of encoder counts registered by the gripper encoder.

Motor speeds

The following are maximum angular or linear speeds.

movement	maximum rated speed	at motor speed
zed	104.2 mm/s	975 rpm
shoulder	42.8 degrees/s	6250 rpm
elbow	85.6 degrees/s	6250 rpm
wrist yaw	128.4 degrees/s	6250 rpm
wrist pitch and roll	92.7 degrees/s	6250 rpm
gripper	84.9 mm/s	6250 rpm

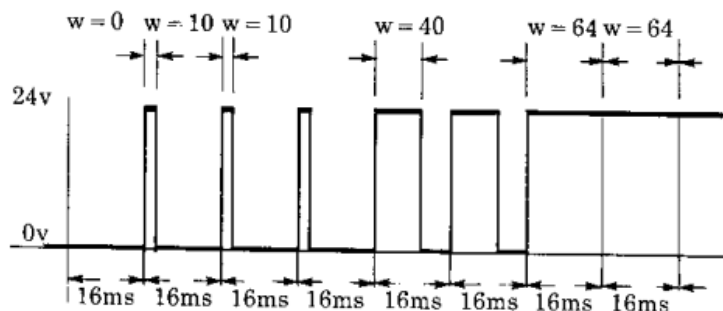
table 8

Lifting capability

The shoulder, elbow and yaw motors do no work against gravity when the arm manipulates load, as they drive joints that swing in the horizontal plane. The zed motor does work against gravity, and can lift 4 kg in addition to the weight of the arm, at 100 mm/s. The wrist motors also work against gravity (the worst case is when the gripper is horizontal), and they can pitch and roll a 2 kg cylinder centrally held in the gripper at 60 degrees/s.

Torque applied to arm joints

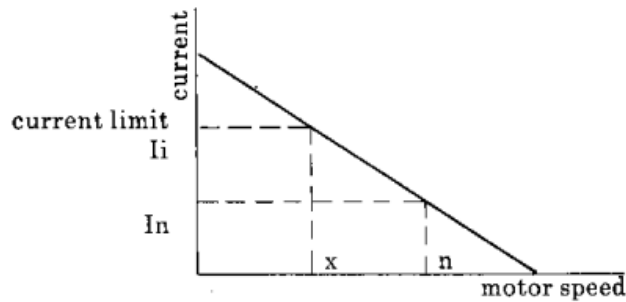
The motors are driven using pulse width modulation. The torques applied to the arm joints are regulated by the width of the pulse of current which is supplied to the motors every 16 ms. The width (w) of this pulse ranges from 0 to 64. With a value of 64, the motor sees a continuous supply of current.



The amount of current drawn by the motor is dependent on:

- ... the speed
- ... the current-limiting circuitry in the motor drive circuits.

The current that can be drawn by the motor decreases in a linear way with an increase in motor speed.



Below speed x the motor is current-limited and the average current seen by the motor is $W/64 \cdot I_i$. Above this speed, the average current is $W/64 \cdot I_n$, where I_n is the current drawn at speed n . Motor torque is proportional to motor current.

The small motor/gearbox output is 100 mNm at 300 rpm for 300 mA, equivalent to a motor speed of 6069 rpm. The output of the large zed motor/gearbox is 4 Nm at 50 rpm for 1.8 A, equivalent to a motor speed of 1250 rpm.

The small motors are limited to about 750 mA, and the large motor to about 3A.

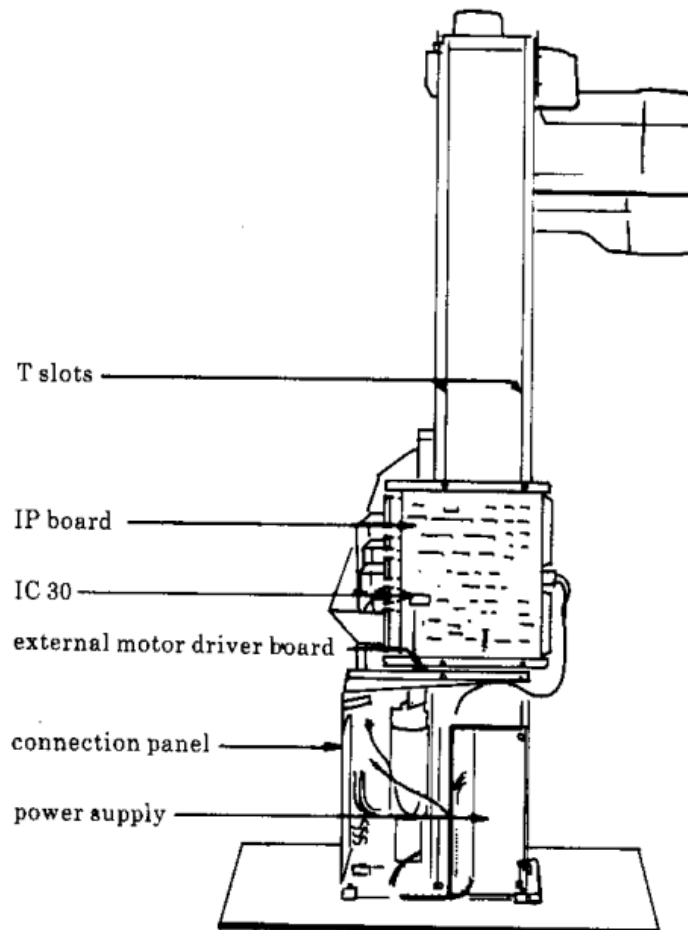
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Repeatability

The repeatability of RTX's movement is typically +0.5 mm at the wrist pivot with the arm at full extension, and with deadbands set to 1 (see servo loop parameters, page 24).

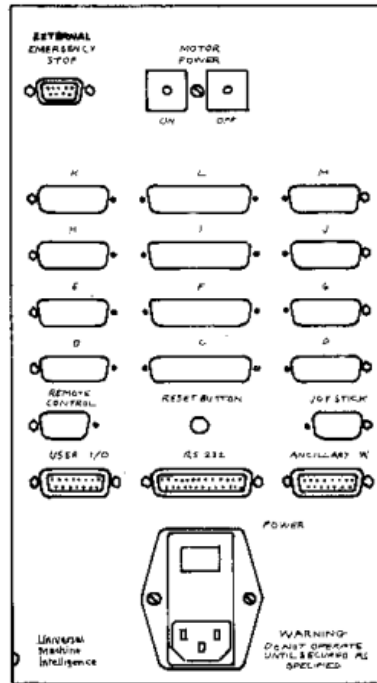
RTX's electronics

The control unit electronics are mounted behind the column. The main controller card is fixed by nuts in the T-slots on the column. The main controller is an IP (intelligent peripheral) board which consists of IP 0, IP 1 and the motor-driving circuitry.



There is also an external motor driver (EMD board) which powers the zed motor, mounted on the side of the column, and a power supply behind the column main support bracket.

The control unit's connection panel is arranged like this:



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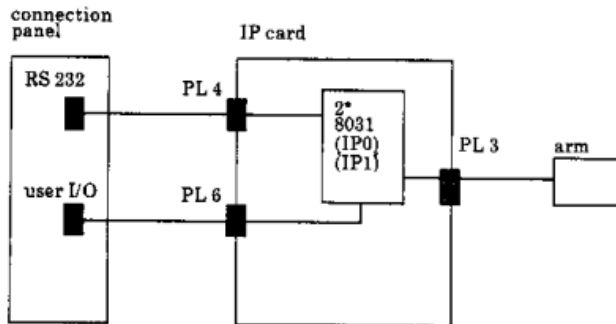
The IP board

Each IP is an Intel 8031 micro controller, with proportional, integral and differential (PID) control algorithm and velocity profiling. Each IP includes an Intel 8156 256-byte RAM with input/output, a 27128 EPROM (which contains each IP's 16-Kbyte firmware), and an 8243 input/output expander.

IP 0 can control the position, speed, acceleration and force of up to five motors; in the standard RTX it controls the zed, shoulder, elbow, yaw and gripper motors. IP 1 can control up to four motors; in the standard RTX it controls the two wrist motors. Two motor axes are available for future expansion.

The motor drivers are Sygnetics L293E chips, each supplying a nominal third of an amp to each motor.

The arrangement of the connection panel, the IPs and the arm is like this:

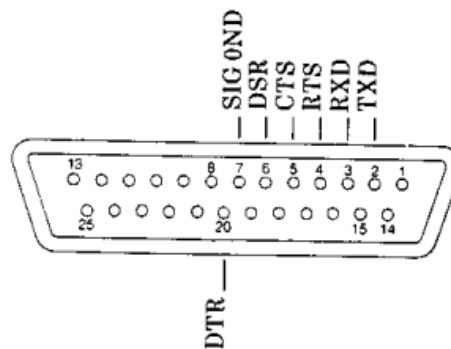


The RS 232 socket links to an RS-232C serial interface:

data rate	9600
data bits	8
parity	even
stop bits	1

table 9

The RS 232 socket is wired like this:

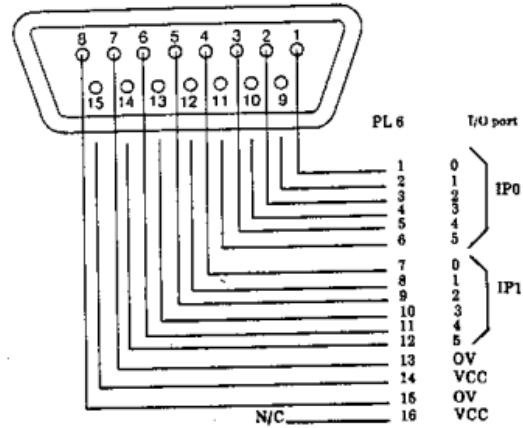


User input and output

Each IP has input or output lines that can be used for switches, sensors or any other device that you might want to add to the robot. Access to the lines is through the USER I/O socket on the connection panel. These lines are TTL levels and should be buffered.

There are six of these lines on each IP. You choose between input or output for the lines on each IP using the SET MODE keyword explained in *Programming using the library and Forth Teach and Replay..*

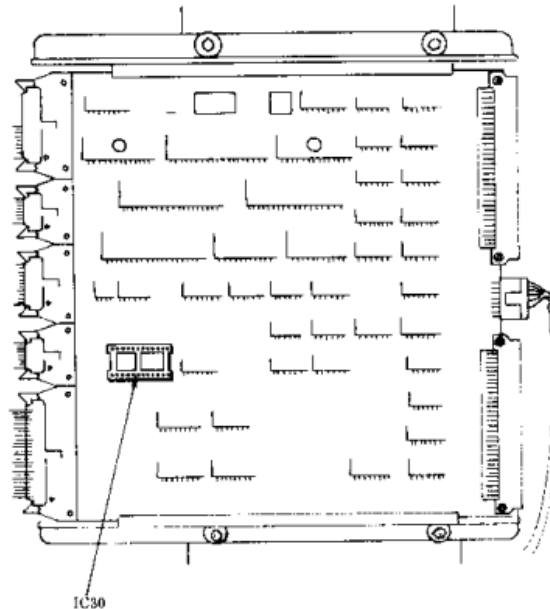
The USER I/O socket is wired like this:



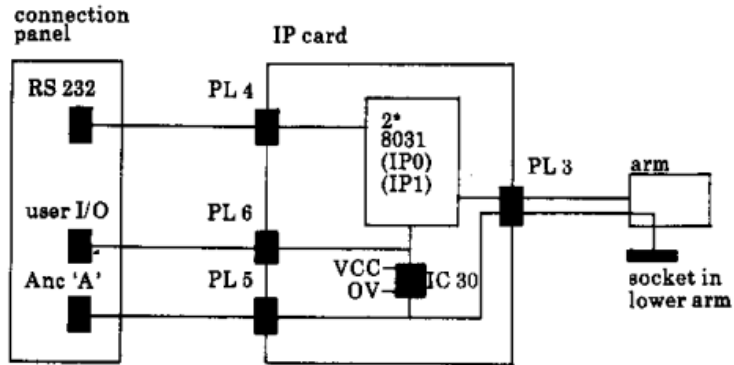
Ancillary connections

In the arm's wiring loom, there are an additional ten wires that link a ten-way socket in the lower arm to the ANCILLARY 'A' socket on the connection panel. The wires are for uses such as linking sensors on the gripper to external devices.

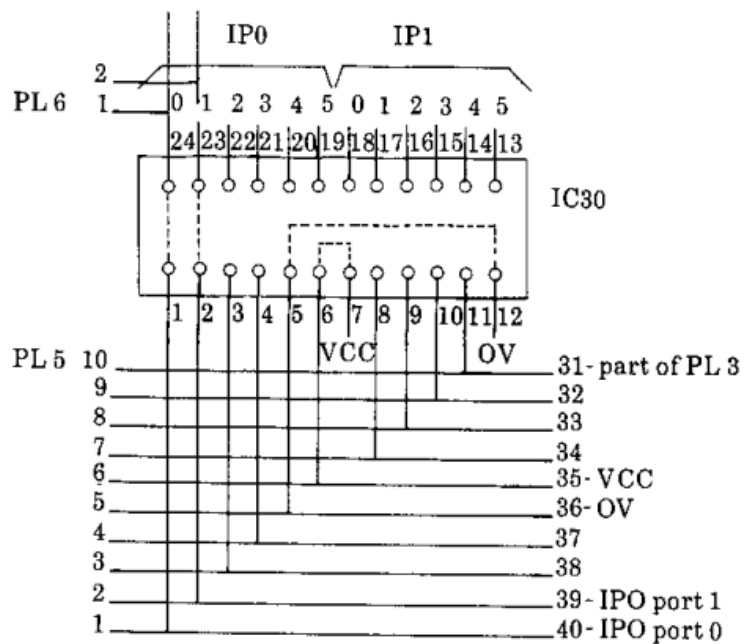
As an alternative to connecting to an external device, it is possible to connect the ancillary wires from the lower arm to the IPs' user I/O ports by making links on IC30, a 24-pin DIL socket on the IP printed circuit board.



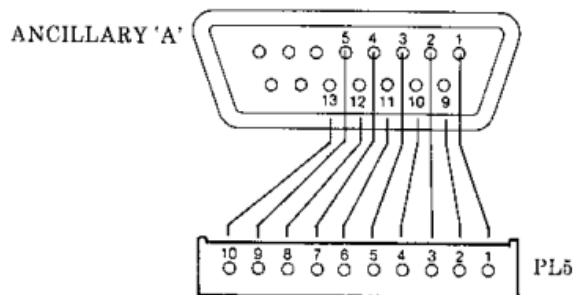
This arrangement is shown in this block diagram:



This diagram shows how the wiring is arranged around IC30. A typical interconnect is shown in dotted lines.



The wiring from PL5 in the IP to the 15-way D-type socket ANCILLARY 'A' on the connection panel is:

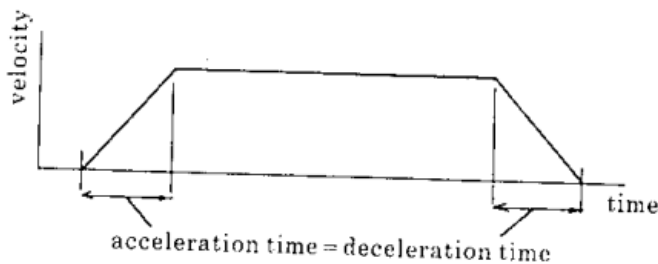


How the IPs control the motors

The IPs drive servo control loops which operate at 62.5 Hz, which means they make a new position demand every 16 ms.

Velocity profiling

When you program one of RTX's motors to move to a new position, the processor in the IP controlling that motor computes a velocity-versus-time curve for the motion. This process, called velocity profiling, is performed by software called a velocity profiler. The curve is trapezoidal in shape:



The shape of the velocity versus time curve depends on two control parameters stored in the IP: ACCELERATION TIME and SPEED. (SPEED here means the maximum attained speed.) These parameters have sensible default values for all motors, but you can set them yourself if you wish.

The velocity profiler divides up the curve into distances for the motor to move every 16 ms. These distances are passed on to the servo loop for the motor concerned.

The servo loop then tries to fit the actual motion of the motor to the curve generated from the velocity profiler.

The servo loop parameters

This section assumes an understanding of servo control theory.

The servo control of the motors is by proportional, integral and differential terms which can be fixed by the controlling computer. Offset and deadband terms are also needed, the former to overcome the friction of the motor and the latter to give a range within which RTX will assume it has reached its destination.

The output of the servo loop to the motor is a pulse of current, of fixed amplitude but with a width ranging from 0 to 64 units. The maximum width of 64 units means that current will be supplied for the whole of the 16 ms time slot.

The current supplied to the motor depends on the five control parameters mentioned above, and also on the error returned from previous cycles. This error is listed as the control parameter ERROR, but it can only be read and not written to. It also depends on MAX FORCE in that this is the largest pulse width that will be supplied, regardless of the demand made by the servo loop.

The relationship between the width of the pulse (w) and the control parameters is:

$$w = \left(\frac{KD}{16} \cdot \text{differential} + \frac{KI}{4096} \cdot \text{integral} + e \cdot \frac{KP}{256} \right) * 2 + \text{OFFSET}$$

where e is the error.

KP, KD, KI, OFFSET and DEADBAND can have values in the range 0 to 240. If e is less than or equal to DEADBAND then w = 0.

The IPs are programmed to give the following default values to these parameters when powered up:

parameter	default for motor							
	Z up	Z down	S	E	Y	W1	W2	G
ERROR	-	-	-	-	-	-	-	-
CURRENT POSITION	0	-	0	0	0	0	0	0
ERROR LIMIT	200	-	200	200	200	200	200	200
NEW POSITION	0	-	0	0	0	0	0	0
SPEED	50	-	100	100	100	100	100	100
KP	100	100	115	115	75	60	60	50
KI	78	78	90	90	15	9	9	6
KD	78	78	25	25	23	35	35	15
DEAD BAND	1	1	1	1	1	1	1	1
OFFSET	0	0	3	3	5	3	3	5
MAX FORCE	64	-	64	64	64	64	64	64
CURRENT FORCE	-	-	-	-	-	-	-	-
ACCELERATION TIME	10	-	10	10	10	10	10	10
ACTUAL POS	-	-	-	-	-	-	-	-
STATUS	-	-	-	-	-	-	-	-


table 10

These values will give smooth control of the arm under normal operation.

Some of these values may change.

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Warning

This equipment generates, uses and can radiate radio frequency energy and if not installed and used in accordance with the instruction manual, may cause interference to radio communications. Most importantly, the equipment must be used with the supplied cables and with covers securely fixed in position. Any additional cables (user I/O, emergency stop, etc.) must be obtained from the supplier or made to the equivalent specification in order to maintain FCC emission limits.

This equipment has been tested and found to comply with limits for a Class A computing device pursuant to Subpart J of Part 15 of the FCC Rules, which are designed to provide reasonable protection against such interference when operated in a commercial environment. Operation of this equipment in a residential area is likely to cause interference in which case the user at his expense will be required to take whatever measures may be required to correct the interference.

