Finger area	35 cm^2
Maximum finger force	350 N (full finger area engaged)
Speed of finger closure	8.5 cm/s
HAND Rotate stall torque	45 Nm
Rotate speed (no load)	10 rev/min (continuous)
Telescope stall thrust	200 N
Telescope speed (no load)	12 cm/s
Stroke	9 cm
WRIST Torque	55 Nm
Speed	2 rev/min max. (hemispherical coverage)
ELBOW Torque	165 Nm
Speed	0.75 rev/min max. (hemispherical coverage)
SHOULDER Torque	330 Nm
Speed	0.33 rev/min max. (hemispherical coverage)
Arm clearance	16 cm diameter hole

The Self-Propelled Anthropomorphic Manipulator or Sam[103] which was built at low cost, is a four-wheeled, remotely controlled vehicle carrying an articulated arm mounted on a semicircular track. The manipulator can operate from ground level to nearly 2 m above the ground. The manipulator arms are Rancho Los Amigos orthotics and they are remotely controlled by an exoskeleton worn by the human operator. The operator wears a head harness which controls a T.V. camera carried on the manipulator. Command and control is carried out via a commercial 64-channel PCM-FM radio link.

The Mascot mobile manipulator[7–11]

Some of the most outstanding results with mobile manipulators have been produced since 1959 by the Servomechanism Laboratory of the National Committee for Nuclear Energy (CNEN) at Casaccia Italy, under the direction of Carlo Mancini. This work will be described in some detail here, since it provides an excellent model for future work on independent robots. Based on the earlier work of the Remote Control Division of CNEN, the research culminated in the production of the Mascot mobile manipulator, which is now made commercially by Selenia of Rome. The name Mascot is short for MAnipolatore Servo Controllato Transistorizzato.

From the start Mascot was designed on an engineering basis. It was estimated that the cost of covering a working volume with a mechanical form of manipulator was about 1000 dollars/cm^3. Since the cost of any mobile robot type of manipulator was initially estimated at about 50 000 dollars, it would have to be capable of covering a minimum working volume of over 50 m^3. It would also have to be capable of handling a work load of 23 kg and of lifting the load to a height of 4 m, and have a dexterity comparable with that obtained with a mechanical manipulator.

The mobile slave equipment was mounted on a remotely controlled trolley powered by electro-hydraulic actuators, and it was also to be provided with a stereo T.V. camera. Each of the two arms has seven possible motions: three in translation and three in rotation and the seventh is the squeeze motion.

A notable engineering feature of Mascot is that identical modular servo controls have been used for all of the seven movements of each arm. Stabilisation of the servos is by feedback of a velocity signal. It is of interest here to give the specification of the standardised servo system:

Maximum torque	20 Nm
Maximum speed	70 rev/min
Maximum self-synchronising angle	2.5 rev
Starting friction torque	0.1 Nm
Compliance	0.002 rad/Nm
Bandwidth	25 Hz
Full load damping factor	>1

The two-phase motor used in the servo system was specially designed and built. The specification is as follows:

Supply frequency	50 Hz
Stall power per phase	180 W
Maximum torque	0.5 Nm
No load speed	2900 rev/min
Stall acceleration	80 000 rad s^{-1} s^{-1}
Friction torque	0.001 Nm

Both the motor and the controller were designed for continuous duty with maximum applied torque, an air flow of 30 m^3/min being required for cooling the motor in an ambient temperature of 25°C. The fan was arranged to cool the motor whenever a fixed value of temperature is obtained. The average temperature of the motor is minimised by controlling both fields simultaneously, rather than just one, and this helps to increase the motor life. The maximum power output from each of the channels is 500 W.

Great care was taken with the construction and with the materials used in the early Mascot. For example, stainless steel control cables, corrosion-resistant aluminium and radiation-resistant greases were used. The tension of the operating is maintained, despite movements of the relative positions of the lower and the upper sections of an arm, by the use of special cams.

The feature of failure to safety was included, all motions being automatically locked by switching off an electromagnetic brake release and so allowing a spring to operate the brake in the event of failure. A failure is indicated either by an increase of the main synchro control voltage above a preset maximum value or by a decrease of this voltage to zero.

The weight of the slave unit is 775 kg, the over-all size being 125 cm × 110 cm × 170 cm. The maximum speed at which the tongs can move is 75 cm/s, with a starting friction of 0.25 kg and a compliance of 2.8 cm/kg.

As a result of this work, it was suggested that the speed and sensitivity of the movement should be increased, that the servo friction should be reduced, and that the steel operating cables should be replaced by tapes.

In the early work the weights of the arms were balanced by counterweights, and this method had the disadvantage of increasing the inertia of the system. In later work the weight was balanced electrically with torques generated by the servo driving units. The new approach also gave greater freedom in the design of the arms. The friction and the inertia of the arms was largely due to the servo drive units, and these factors were also reduced by the use of feedback torque signals. Such methods have improved the feel of the system to the operator, under both dynamic and static conditions.

At the same time, the required number of leads between the master control unit and the slave unit was reduced. This gave a greater flexibility of movement to the slave unit. In addition, the dimensions of the servo drives, and therefore of the arms themselves, were decreased. This had the incidental advantage of improving the versatility of the system, since a wider range of tasks could be undertaken with a smaller unit.

The power amplifiers which have been used on the later devices are of the switched high-efficiency type, with natural cooling. One object of the adoption of the new forms of power amplifier is a reduction of the size of the control power amplifiers to the point where they can be installed directly on the body of the robot rather than remotely. Since only the low-power control signals then have to be taken to

the robot unit, smaller and lighter trailing cables can be used, and eventually it is hoped that the complete flexibility of radio control of an independent robot can be used.

Later Mascot work[12, 13]

No attempt will be made here to present a comprehensive treatment of the methods used on Mascot. A very thorough treatment is given by the publications of the Italian workers, who have clearly taken pains to make sure that the information is available to all.

On the later work on Mascot the two-phase servo-motor was used for the following reasons:

1. The motor is rugged and requires little or no maintenance.
2. The ratio of maximum output torque to friction torque is high. This leads to a high system sensitivity.
3. The drive is smooth, since the torque is constant over the whole revolution of the motor shaft.

Instead of a single larger motor for the drive, four coupled motors are used. This leads to a compact arrangement with a reduced over-all moment of inertia and an increased surface area for heat dissipation, permitting a high value of overload capacity. The motor supply is 115 V, 60 Hz, and the other details of the standard motor are:

Maximum control phase power	33 W
Starting torque	0.1 Nm
No-load speed	3500 rev/min
Starting acceleration	34 500 rad^{-1} $^{-1}$
Power output	10 W

The maximum control winding voltage is 150 V, while the reference winding is normally operated at 100 V, being switched up to 150 V when maximum torque is required. The maximum power dissipated is 70 W at full voltage, falling to 25 W at rest. The slave servo drive unit output torque is a maximum of 20 Nm, and it can be maintained for 15 min at an ambient temperature of 20°C.

Position measurement is by means of a variable phase signal from a 400 Hz linear synchro, the range being $\pm 60°$. The synchro is supplied with a frequency of 2 kHz, the same supply being used for the two-phase tachometer generators used for speed signals. Compared with the earlier Mascot arrangement, the total number of leads between master and slave is reduced from 55 to 33 by the use of the new arrangement. Tests with film potentiometers for position measurement were unsuccessful.

The drive motors are built directly on to the drive gear-box, a reduction ratio of 38: 1 being used between the motors and the output shaft, while a ratio of 10:1 is used between the output shaft and the linear synchro. The starting friction torque is 0.03 Nm and the outside diameter of the gear-box is rather over 12 cm.

The servo amplifier details will not be presented here, as they have been given elsewhere. However, the time-division form of power amplifier which was used should be specially mentioned, since this gives a very small and simple arrangement which has low losses and can be cooled by natural convection. The advantages of this system appear promising for eventual use in a power amplifier mounted on the mobile device, controlled by time-division pulses over a radio link. At present up to 300 m of cable can be used.

The research work on the Mascot device has led to its commercial production by Selenia of Rome. In the commercial model it is stressed that the robot is virtually self-repairing, since one of the manipulator arms can be repaied by the other. There are two separate failure-to-safety features. In the event of power failure, the arms and hands are locked in the last position. If there is a minor failure—for example, a failure of the cooling system—the operator is advised 90 s before an automatic shut-down, so that a task can be completed or avoiding action taken. To reduce operator tiring, the feedback ratios used are adjustable, and if required the operator can lock the control loop of one arm by use of a foot control, while he concentrates on the action of the other arm.

The research work leading to the successful production of the commercial Mascot robot manipulator is certainly deserving of great praise, not only for the outstanding engineering results achieved but also for the unselfish way in which the results have been published freely and the way in which the difficulties encountered, as well as the successes, have been openly discussed.

Perhaps the best praise that can be given for the final result is to quote Ballinger[6], who stated that the machine creates a humanistic impression which generates an impulse to speak orders to the machine rather than to the operator.

If future developments go as expected, it will almost certainly be possible to do just that.

Near field control[49]

Where a robot device must be controlled by a human, in some cases

the robot has been linked to the control console by wires. This has the effect of limiting the mobility of the robot and of the operator. It also calls for care in order to avoid the tangling of the control cable. In some cases it has been necessary to arrange for the control cable to drop from overhead to the robot.

Greater mobility of both robot and operator is possible if a radio link is used for control. A typical example with which the writer was associated some years ago was the control of a ropeways trolley on a long track stretching out to sea for oil drilling, the frequency of radio control being of the order of 60 MHz.

Where a robot device must be controlled or communicated with in space, there is, of course, no alternative to the use of radio communication. The problem of delay in the control achieved by this method has been mentioned elsewhere.

There is a large range of robot control and communications problems where the distances involved are only of the order of 100 m at the maximum, but a complete flexibility of movement of the robot and the human (or of a second robot) is desirable. Radio communication introduces problems of finding spectrum space and of avoiding interference. Communication by light waves is not always easy because of the severe directionality. Ultrasonic communication is a possibility, but it does not seem to have been widely exploited except for some applications to crane remote control.

One system ('Telemotive') which overcomes many of the problems in control and communication over distances up to 100 m is the use of near field induction effects at medium frequencies of a few hundred kilohertz. An induction field falls rapidly in strength as the distance from the source antenna increases, being approximately inversely proportional to the cube of the distance from the source. The effect can be detected at distances up to about one-tenth of a wavelength from the source. Consequently, an induction field system is fundamentally ideal for use in the type of application envisaged. Frequencies of 250–400 kHz have been used, the transmitted power being 60 mW and the sensitivity of the receiver being about 0.05 m.V. A range of up to 60 m is obtained with such a system, and repeaters can be used if this has to be extended.

Such a system has been found to give immunity from radio-frequency interference while meeting with Post Office licensing approval. It is possible to design for failure to safety and easy and immediate maintenance by untrained personnel even though the belt-mounted operator transmitter is small and light in weight. The control channels have been spaced by 125 Hz within a total bandwidth of 4 kHz, and one user is said to have 20 systems in use in the same shop, using different carrier frequencies and separation by