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HUMAN-LIKE MACHINES

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ABSTRACT. Applications of Teleoperator machines (remote manipulators) and robots in various areas of technology are described. The Syntelmann Teleoperator is discussed in detail.

The design of human-like or anthropomorphous machines is an old dream of humanity, just as aviation and space flight. The question can immediately be raised of whether a machine must have a human-like configuration. In the course of this report, we will answer this question positively. The answer will be determined exclusively by technical requirements and not by fantasy. Automation of industry has produced circumstances in which humans no longer do the work alone. The working process is divided into several partial processes which can occur without a complete knowledge of all requirements made on the product. The production line is a logical further development in this direction. Work stations and work processes are created which cannot be manned by conventional machines without a great deal of effort and special installations. In these applications, the anthropomorphous machine is a means of increasing productivity and of freeing the human work force from monotonous work so that it can perform work of a greater value. /45**

Advances in technology and the extension of human capacity are limited by physical barriers, on the other hand, which restrict human work or confine it to a certain time interval (for example, in space, in the oceans, or in a radioactive environment). In order to overcome these barriers, machines have

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**Numbers in the margin indicate pagination in the original foreign text.

been designed which can replace his arms, hands and legs, as well as his sensory organs at such locations. These machines consist of a working system which can be used in an environment which is hostile to humans. They also have a control system and regulating system which is located in surroundings which are not hostile to humans. The entire system is called "Teleoperator". The syllable "Tele" means that the system cannot only overcome physical limits, but also can operate at large distances.

The remarkable feature of the Teleoperator machine is the fact that their regulating systems are closed via humans. The system can only react to unpredictable events correctly if humans are included. This represents a significant difference compared with all pre-programmed machines designed for special tasks. Because of its special design, a Teleoperator can be used in many ways. He can do the following:

— Collect rock samples and perform experiments on extra-terrestrial bodies. It can do this even if the conditions on the surface are extremely unfavorable to humans. It can then return back to earth.

— It can perform repairs and maintenance of satellites and spacecraft in space.

— It can perform repairs and investigations at the bottom of the ocean (repair of telephone lines, oil lines and excavation locations).

— It can manipulate radioactive components and atomic reactors.

— It can multiply the work capacity of humans.

— It can replace the human work output in repetitive production processes.

The expression manipulator is often used in this connection. This is only restricted to the working arms and precludes any translation apparatus.

Teleoperators — Robots

Some confusion exists between the term Teleoperator and Robot. In contrast to Teleoperators, Robots are pre-programmed and their work proceeds according to a given working plan. This does not exclude it from gaining experience and then changing its program. Robots require a behaviour pattern. Therefore, they are only suitable for special tasks which are predictable and which repeat themselves. In the case of a Teleoperator, human beings are included in the control system as an active unit, even if subordinate actions can be carried out without the aid of humans. The strategy of the work is always determined by humans. We will explain the difference between a Robot and a Teleoperator by means of an example: If a chain drops off a machine, then the Robot can only put the chain onto the machine if it has already done this once before. On the other hand, a Teleoperator can perform this task without this restriction. Of course, a Teleoperator can be easily used as a Robot if it is controlled from a memory.

Subsystems of a Teleoperator

Four different types of subsystems can be distinguished in all Teleoperators:

— The control elements of the working system which carry out commands of the operator in the hostile environment.

— The sensor system which furnishes the sensory impressions to the operator (vision, hearing, feeling, temperature, electrical fields, etc.).

— The control system which includes the operator. It evaluates feedback messages of the control elements and the sensor system and compares then with prescribed commands. This results in commands to the control elements.

— The information system which connects the operator and the machine.

— Other auxiliary systems are used depending on application and use (energy supply, computer, translation system).

Working System

Depending on the mode of operation of the control elements, we may differentiate between

- muscle driven systems
- electromechanical systems
- hydraulic and pneumatic systems.

Combinations of these three types also occur.

Muscle driven systems refer to a mechanical connection between the master and the slave through a protective barrier. Numerous mechanical manipulators in radioactive areas of nuclear reactors operate according to this principle. One can work rapidly and accurately with these devices. However, they have the great disadvantage that they can only be used at a certain location with respect to the operator. Humans must approach the dangerous area to within a few meters. They cannot be used for industrial applications because they have no drive mechanisms of their own.

Systems, which use electrical motors as control elements, can easily be made to operate independent of their location. On the ground or below water, their energy is supplied by means of a supply cable. In space, it is supplied by batteries and solar cells. High motor rpm and gears are required in order to obtain sufficient torques at low weights. The wide variety of electrical components, and the high packing density in the control system which can be achieved with electronic components, represent some of the advantages of these systems. Compared with muscle driven or hydraulic and pneumatic systems, electromechanical systems are less sensitive to environment (temperature) and disturbances. The control of the mechanical arms can be by means of a direct electric circuit, so that only electromechanical energy converters are

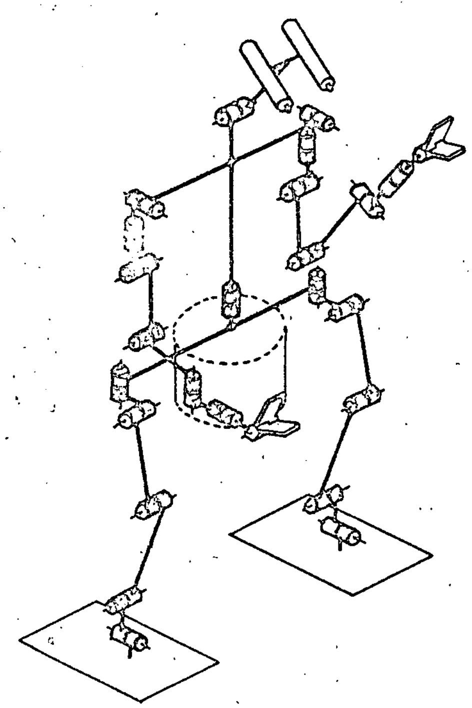

Fig. 1. Joint system of a anthropomorphous, two-legged Teleoperator.

necessary. At a distance, the system is only limited by the finite velocity of light and the associated retardation in the signal transmission.

Pneumatic and hydraulic systems can easily produce the required large forces and slow motions. They cannot be controlled as sensitively, the control channels are sensitive to disturbances, and they depend strongly on the temperature of the work medium. In addition, the systems must carry along their working medium or take it from the surroundings. Therefore, they are not as well suited for mobile applications as are electrical systems. They require electro-hydraulic-mechanical converters.

Anthropomorphous machines represent a greatly simplified model of the human body or of its parts which it must replace. The similarity to humans is only a consequence of the requirement for a large variety of applications and easy controllability of the machine. Figure 1 shows a "Syntellman" Teleoperator built according to this principle by Prof. Dr.-Ing. H. Kleinwächter. The translation apparatus consists of two legs with carry the two working arms and the head which contains sensory organs, especially the television eyes.

Humans are different from other living organisms, not only because of their much more powerful brain, but also, due to the hand which can be used in a large variety of ways. The possibilities of motion of the human arm and hand are very great. Each arm consists of 30 bones which are connected by joints to a greater or lesser extent. 27 of these are located in the hand. This complex is driven by 60 muscles. The direction change capacity of a

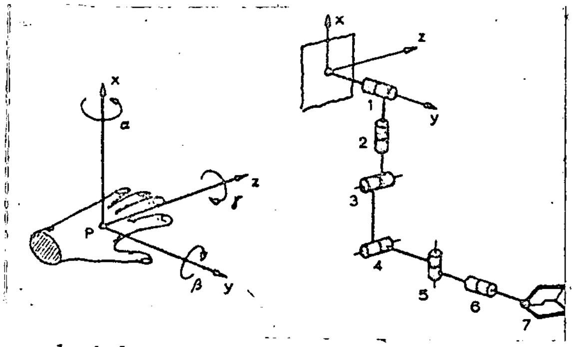

Fig. 2. Necessary number of degrees of freedom of a mechanical arm.
1, 2, 3 — shoulder joint; 4 — elbow; 5 and 6 — hand root; 7 — hand tongs.

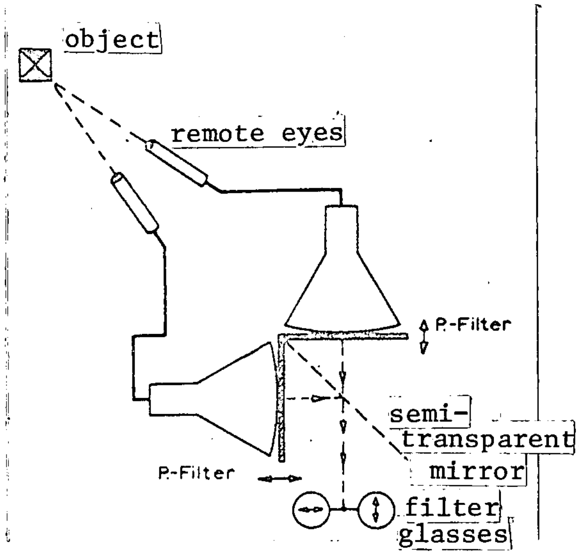

Fig. 3. Stereo television system with polarized optics.

joint is known as its degree of freedom. Thus, for example, a spherical joint such as the shoulder joint has 3 degrees of freedom. If we consider the human arm and design a mechanical arm according to the same principle, then we arrive at a design shown in Figure 2. If the hand joint of the arm is to take on any orientation in any position in a certain region of space, then the arm must have 6 degrees of freedom. These are the three Cartesian coordinates x, y and z, so that any point in space can be established. The others are the three angular degrees of freedom (pitch, yaw, and roll angle), so that the hand can take on any arbitrary orientation in space. In order for the manipulator to perform work with the hand, it must have a further degree of freedom in the simplest case. Thus, we obtain at least 14 joints which can be controlled independently of one another for a two-arm manipulator, which requires 6 drive motors. If the arm is to carry out motions with a great degree of accuracy, then there must be very little play in the joints, because a joint is based on a previous one and the errors add up.

Sensor System

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The working range is covered by means of various sensors which replace the various types of sensory organs. For a Teleoperator, the optical feedback is the most important function. A stereo television system produces a three-dimensional picture for the operator. Figure 3 shows a diagram of a spatial system. Pictures from the left and right television eye are separately directed to the left and right eye of the master by means of two separate television channels. Two separate television monitors are used for this purpose which are observed through a semi-transparent mirror using two polarization filter pairs. A three-dimensional impression of the working area is produced in the brain of the master. Other sensors produce the feedback of the finger forces and the forces in the arm. The signals from these sensors are especially important if the system is to be used in industrial applications. The sensory organs also include touch sensors, temperature sensors and microphones.

Control System

Various types of control of a Teleoperator exist:

— The joints are turned on or off by means of a switch. Only one joint can be precisely activated. The manipulation lasts a long time if it can be done at all. Two arms cannot operate in conjunction.

— Proportional control using the potentiometers. The joints operate and their velocity is controlled. The precision and rate of work are greater than for the switch control method. However, it is still true that only one and a maximum of two joints can be operated accurately.

— Velocity and position control: using a joint system (exoskeleton) strapped to the human body (master), the motions of the master are converted to electrical signals which control the Teleoperator. All motions of the master are performed simultaneously and with great accuracy. Using this anthropomorphous control, it is possible to operate 14 and more drive joints of the Teleoperator in a decisive and accurate way without any learning process. This of course requires a high degree of accuracy and precision of the control elements and their control systems.

The Syntelmann is a typical example of this highly developed type of Teleoperator which can perform complicated work using two arms.

— Coded signals: This is the best suited type of control for industrial applications. The work process is read into a motion storage unit by means of an exoskeleton which then, later on, performs the work by itself.

Information System

This subsystem has the task of directing the data and control commands to the correct address and transferring them there. This is done either by radio or using a wire connection. In order to save communication channels, a multiplex method is used. Most of the transmission band width is used for the video signal from the stereo cameras. The computer is often used for complex systems, in order to perform data compression and coordinate calculations or to control subordinate control circuits.

Applications

Certain technical work can only be performed by using teleoperators. We would like to point out the discovery and recovery of the lost American H-bomb in 1966 off the coast of Spain. There are also the investigations of the Surveyor and the Lunakhod on the moon. These automatic spacecraft are much cheaper than using humans and they are connected with less risk. Often, they can be used much more extensively than humans as far as stay time, distance and possible conditions of the surroundings are concerned. All these examples are restricted to the one-time application of devices for tasks which could not be solved otherwise. This is different if a Teleoperator can replace the human working force in connection with a storage device and thereby increase productivity. In this case, the machine must perform work which has already been done faster, with more safety, and therefore cheaper than possible before.

In the following, we will now describe the technical applications and limits of a Teleoperator built according to the principle of the Syntelmann Teleoperator. Following are some data regarding the system.

Syntelmann

The name is derived from the abbreviation for synchronous-tele-manipulator. The second "n" was added in order to refer to the human configuration. Figure 4 shows the master-slave system. By means of an exoskeleton strapped to the arms of the master, the master controls the corresponding members of the machine-slave. The joint angles of the master are detected electrically by means of sensors and are introduced into control loops as nominal values. The control loops consist of the slave joint and the measured value transducer. The response sensitivity of the system must be great and it must have favorable start-up behavior, because the joints and therefore the control circuits depend on each other. Except for the hand pincers, all joints are position controlled. The joints consist of fast electrical motors which must be greatly reduced in order to produce the required slow motions and the high torques. The extended arm is capable of lifting 25 kg using currently available disc wheel motors and a gear reduction of about 1,000. The pincer force amounts to a maximum of about 50 kg. Improved gears would have to be used to increase the values if the size were to remain constant. This is why most of the work is going on in this area at the present time. The most important feature of the Syntelmann system hand is the wide dynamic range. The master can cover a well defined force range between 0.05 to about 50 kp without switching.

In Figure 5, the hand is compressing a ring with a pincer force of about 40 kp. Of course, the master has to exert a 40 kp force to do this. A function transducer is used to transfer the force. The function transducer has a linear characteristic in the lower range and a progressive characteristic in the upper range.

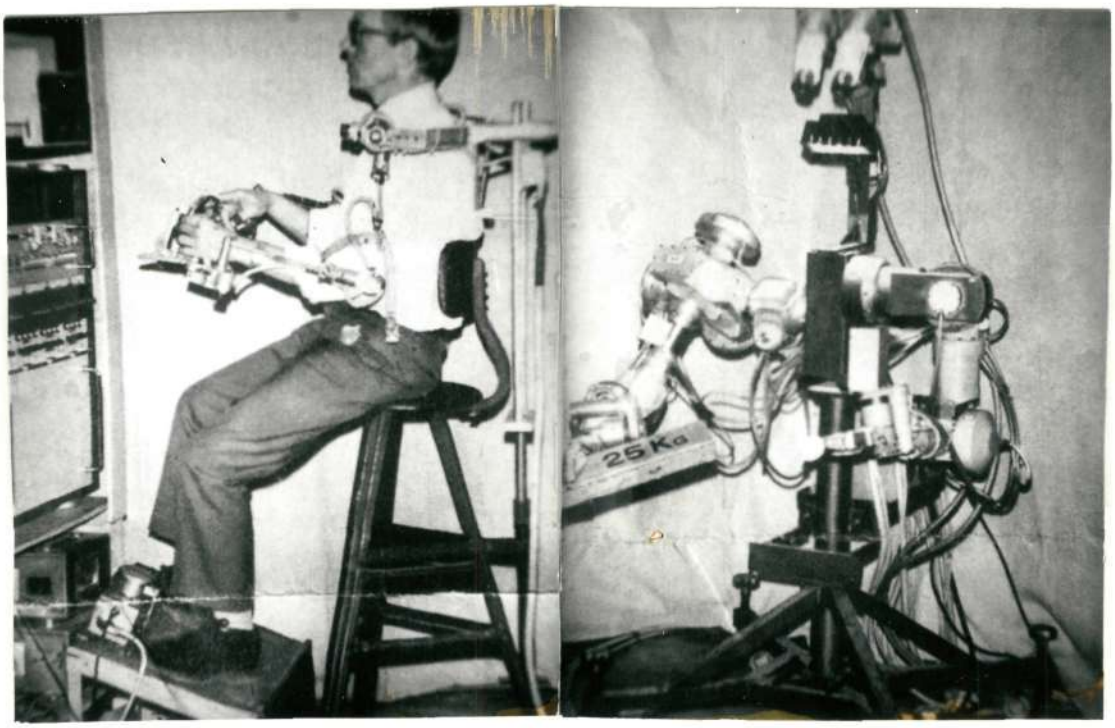

Fig. 4. Master-slave-system of Syntelmann. Left, master with fastened exoskeleton; right, slave with egg and 25 kg load in each hand. Visual control using two-eye stereo television.

An exact measurement of the finger forces and accurate feedback to the master are required for fine manipulations. Measurements are performed using strain gages. These are so sensitive that the master can transfer an egg from one hand to the other without crushing it. Other force measurements at various locations on the arm prevent the system from destroying itself or its environment in case it encounters obstacles. The torque, and therefore the joint force, are limited. When large forces are used which could destroy the system, the arm moves in such a manner that the permissible loads are never exceeded. This is not done using sliding clutches, because this would bring the master-slave system into a position which could not be controlled by the master. Instead, the forces are measured and the information is evaluated electronically. The evaluation circuit then controls those joints which have to yield to the external forces in order to avoid destruction. The completely electrical system is the reason for the great accuracy and fine manipulations which the system can perform. The entire machine only requires a single phase alternating current (220 V/16 A) connected to the net. By using modern electronic components and pulsed control of the motors using triac switches, the loss power amounts to a few watts. If the system is mounted on a remote control vehicle, as shown in Figure 6, a device is obtained which can be used in many ways. The traction vehicle was made available to the Institute by the French Atomic Research Center of Saclay. With this vehicle, it was possible to carry out work in other parts of the building, such as, connection of pressurized hoses, filling of liquids, or connecting and disconnecting connectors. The apparatus was capable of opening doors for itself.

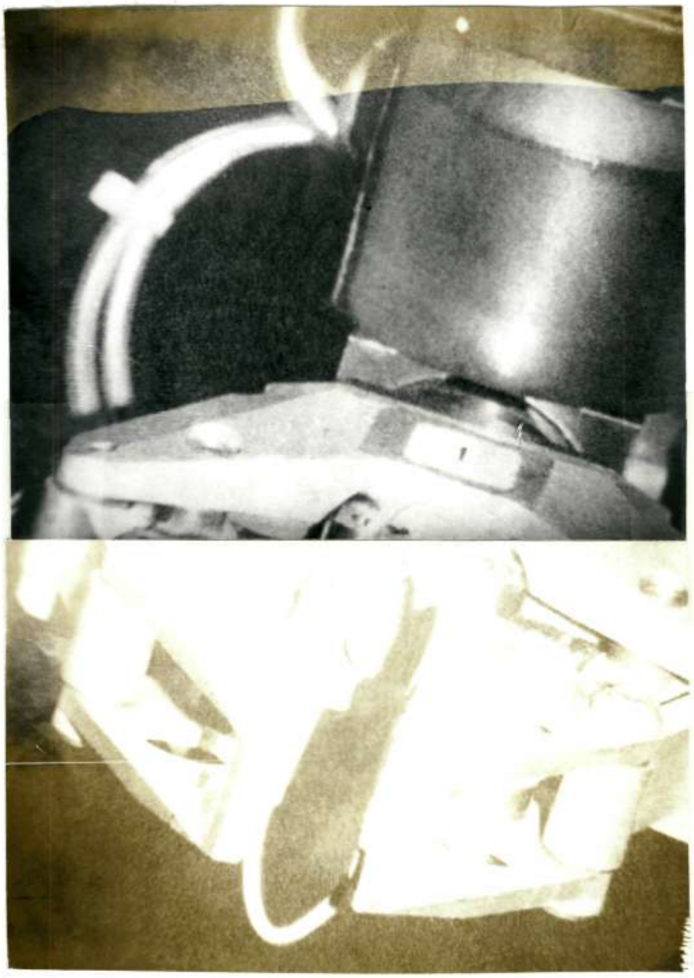

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Fig. 5. Force regulated parallel surface hand tongs. Maximum hand force for compression of the ring, 50 kg.

Industrial Use

Such a complex and many faceted machine has a wide range of applications in industry. Periodically repetitive work processes are a requirement for its use. Depending on the associated intelligence (storage or computer), it can perform advanced tasks. No requirements, due to machines, must be imposed for completing the task. The machine is programmed and repeats the work function by itself.

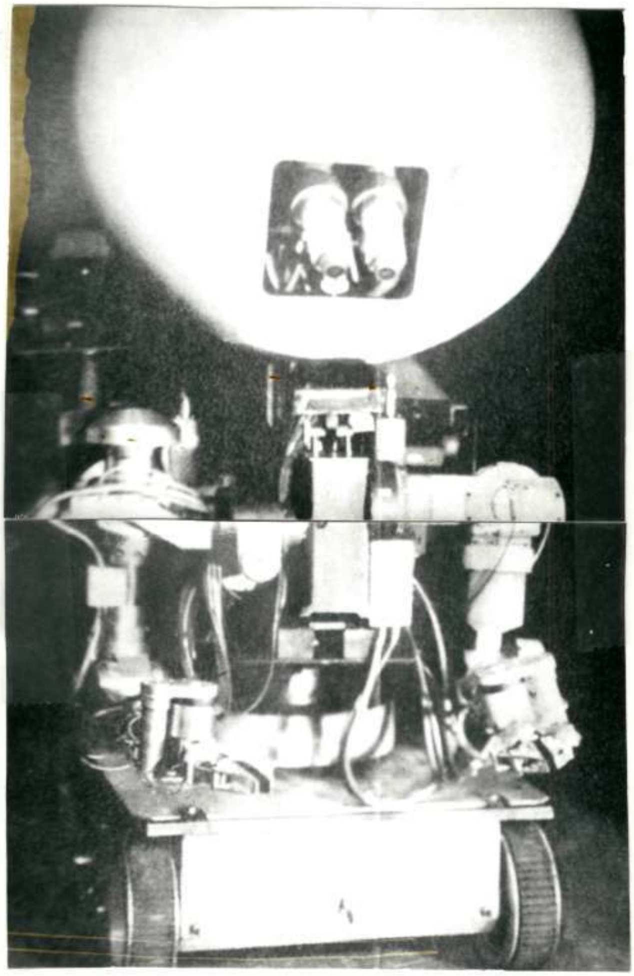

Fig. 6. Syntellman mounted on a remote control vehicle.

The program is input into the storage in two ways:

— Coded, for example, by specifying the coordinates,

— Using the motion of the model.

Usually, the second method is easier to implement. Humans first carry out a model motion which is recorded by the storage system. The machine automatically performs repetitions and sometimes at an increased rate of work. The special advantage of using human-like machines in production is their versatility. They can be easily changed because only the contents of the storage system must be changed. In contrast to automata, which are used for certain tasks, no mechanical changes are required when a production process is changed. A magnetic tape recorder is used as the work program storage and the tape can be easily exchanged. When repetitive lots are processed, only the tape is exchanged and the change-over time is very small.

A manipulator operates just as well as a human if exchangeable and commercial machines are used (such as the drilling machine shown in Figure 7). The transportation of work pieces and the loading and unloading functions are especially important applications in production. The system is also applicable to welding work, as is shown in Figure 8. By measuring the distance

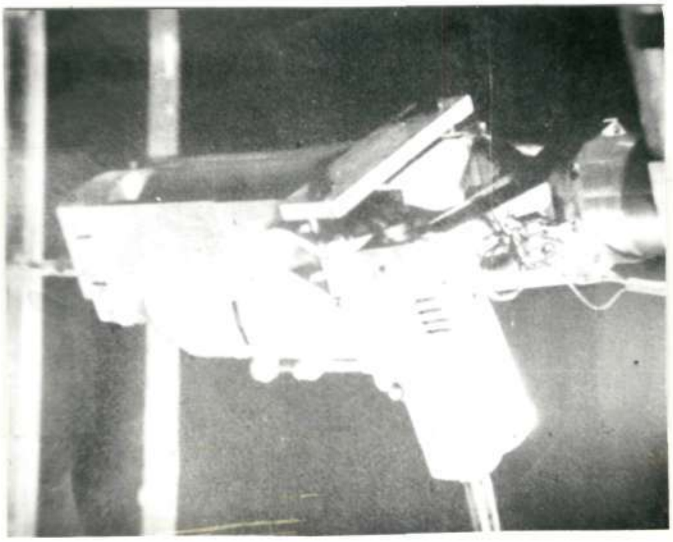

Fig. 7. Manipulator with conventional drill.

Fig. 8. Manipulator, flame cutter in the right hand and 25 kg weight in the left hand.

from the surface, the correct distance to the work piece is assured.

The commercial importance of these systems is easily grasped from these few examples. These will increase in number in the future, because, as wages increase and there is an increased shortage in the work force, humans must be saved for more advanced work. The use of the versatile industrial Robots represent an important step in this direction.

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