

Strain gages as sensors for controlling the manipulative robot hand OEDIPUS

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OEDIPUS is the name given to a project to develop a universal two-finger gripper for a robot hand with four independent degrees of freedom of movement. The gripper is equipped with four position control circuits and a force control system. Two strain-gage transducer systems on the first elements of the gripper determine the direction, magnitude and point of application of the applied force. From these, the system then derives the ideal gripping force which it then applies through the control system. Operations such as tracking of the gripper force for changing external forces are also possible. The article describes the complete project including the force control and gives details of the arrangement and wiring of the strain gages on the elements.

Introduction

For some years now the Austrian Space Agency has been intensively involved in the development of intelligent gripper systems for applications in robotics. From the studies on the application of robots on manned and unmanned space stations, techniques have been developed which may also be significant for certain terrestrial applications. In many fields of flexible automation traditional force and positive locking systems cannot really fulfill the requirements of the next few years. Therefore, a gripper was to be developed featuring high flexibility for all gripper operations coupled with touch sensors.

Applications in space

Within the scope of space technology four main technological fields have been defined involving a longterm demand for robotic applications of manipulative end effectors. These are engineering and biological experiments in a weightless environment, the remote control of extra-vehicular activity, the coupling of space vehicles to space stations (rendezvous and docking) and the remote control of robots for the operation and servicing of space stations.

This requirement is to be fulfilled in the medium term up to the year 2000 on HERMES, COLUMBUS and Shuttle flights. In the long term there will be robotic requirements in the field of interplanetary missions, for sample extraction equipment and for automatically operating probes.

Apart from the requirements specific to a space environment, e.g. compatibility to weightlessness, the demands made on robotic applications up to the end of the '90s are likely to move within narrower limits than previously thought.

First of all, there are the simplest of movements and manipulation functions which must fulfill the primary requirement of the greatest possible reliability and freedom from intervention. They must also conform to the economic restraints governing the complete system. In the first phase of about 10 years, experience in space robotics is to be gathered using simple systems. However, it is also planned to make industrial use of various types of space stations in which it would be practically impossible to carry out the wide variety of tasks using simple manipulators.

Universal functionality of the gripper

The advantage of a robot compared to a simple manipulator is its freely programmable controller. It is therefore possible to carry out a wide range of tasks with the same unit. New movement sequences can be defined just by changing the program without any mechanical modifications being required.

The current state of industrial manipulator technology has to date not progressed very far. In the majority of manipulation and assembly applications grippers are designed specially for a specific task. If changes occur to the system environment or the grippers must be adapted to a new field of operation, then they must be modified or even redesigned.

An initial step in the direction of universality was made through the development of grippers of modular construction. The closed and open angles were set by the adjustment of limit switch positions on the hydraulically or pneumatically operated two-jaw gripper. The grippers were then adapted to the shape of the workpiece using interchangeable jaws. In spite of this, the universal application of this type of gripper is restricted, because it needs mechanical modification whenever there

are changes to the system environment. However, flexible systems make use of rapid change systems similar those found on machine tools. These are capable of a succession of different operations, but have proven to be relatively slow due to the time required to change the tool. In addition, each individual tool is matched to its task and therefore the flexibility of these systems is also limited.

On account of the limitations in mass imposed by space technology, the use of a number of gripper tools is restricted. Here there are two possibilities: either the objects to be manipulated are fitted with a gripper interface so that the gripper can lock onto the interface or the gripper is able, within certain limits, to handle predefined shapes and sizes, leaving some degree of leeway for unplanned events or short-term changes.

A universal gripper is able to carry out the most varied gripping, measuring and joining operations and, with suitable software, it can be applied quickly and flexibly to completely different tasks. This gripper would form the ideal complement to a robot, because then a system would be available that would be able to fulfill new tasks simply by a software modification.

Current state of technology

The main problems involved in designing a universal gripper are that the objects to be manipulated are still in the development phase and are not yet therefore known. Their orientation in the gripper should, however, not be allowed to change or, if this does happen, it is detected and the supervisory control units are then informed. This process must run taking into account the physical limits, such as for example the constraint that neither the object nor the gripper should be damaged by the gripping operation. Also, the detection of the object orientation relative to the gripper is very desirable, especially for joining and for centering the object within the gripper.

Basically, there are two methods of gripping an object. Either the shape of the object can be accommodated or the force is controlled. Universal grippers which adapt to the shape of the object use chains, bands or diaphragms to wrap round the object or to bed it in. This technique has the advantage that the grip is very strong, but these types of gripper are mostly of a large volume and it is not possible to detect the orientation, because too many degrees of freedom would have to be measured.

With the second type, the force-controlled gripper, designs are sought which are similar to the human hand. In this case, a number of fingers, each with a number of degrees of freedom are used. Using position control circuits, it is possible to control their sequence of movements as for freely programmable robots. In order for such a gripper to be able to grip an object, there are two fundamental problems to be solved. First, suitable gripping points must be found which enable a stable state of equilibrium to be achieved. Secondly, an adequate force must be determined and exerted within the position control, so that this stable equilibrium is maintained.

The project

Since the sensor design defined by ORS did not include visual evaluation, the project was named OEDIPUS after the blind hero in Greek mythology.

OEDIPUS is a two-finger gripper with four independent degrees of freedom of movement. It is equipped with four position control circuits and position acquisition. Two transducer systems measure the applied force in terms of direction, magnitude and orientation. The force control system acquires the resulting, external force on the object and optimizes the gripper force referred to the external force. An object which is being gripped can be assigned and recognized based on its size (gripper position), weight and compliance.

A fundamental gripper problem is the determination of the ideal gripper force which is only possible if the external force is known. If the analysis of each individual manipulatory task, common with task-oriented grippers, is to be avoided, then it is essential that the external force is directly measured.

Now for the first time, the theory has been able to be implemented by measuring the force in the first gripper elements in the OEDIPUS project. Difficult operations such as the tracking control of the gripper force resulting from a varying external force have only become possible using this system.

Force measurement

In the process of gripping and holding objects the determination of the forces which are involved is of decisive significance. Here above all, the forces acting on the limbs together with the points at which they act and the direction must all be measured.

This is achieved using strain gages applied in a suitable manner to the finger elements. Precise localization of the points at which the forces act can be obtained by the addition of pressure measurement film on the ends of the elements. The combination of various force measurement systems enables accurate measurements to be made which in turn leads to an increase in the sensitiveness of the gripper system.

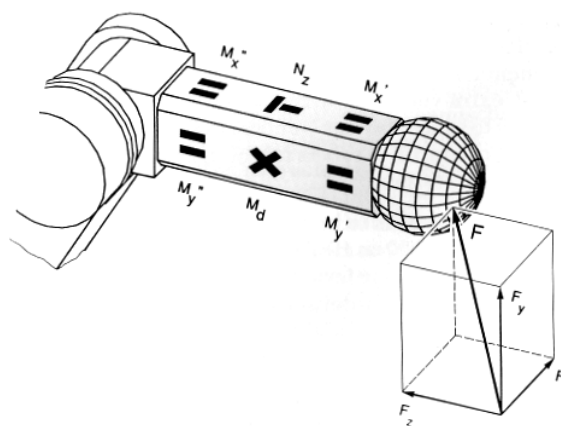


Fig. 1: Resolution of a random force F acting on the end element of the gripper into components of a Cartesian coordinate system.

The additional application of wrist sensors would lead to an increase in the redundancy in the force measurement system. Also, a comprehensive control could be achieved for impermissibly high forces and torques that might be applied anywhere on the gripper System.

Wrist sensors were not applied, because at least partial monitoring of damaging forces and torques is possible with the measurement system installed on the ends of the fingers. The application of wrist sensors would also have meant a severe increase in the overall weight of the gripper system.

Strain-gage measurements

In principle, forces from any direction can act on the gripping surfaces of the gripper. These give rise to various mechanical loads, both in the first element and in the end element. These loads are tensile or compressive stresses in the longitudinal direction as well as bending and twisting stresses.

<p>Longitudinal stress:</p> $\sigma_N = f(F_z) = \frac{1}{A} [F_z]$
<p>Bending stresses in the y-z plane:</p> $\sigma'_{bx} = f(M'_x) = \frac{1}{W_x} [y F_z + z F_y]$ $\sigma''_{bx} = f(M''_x) = \frac{1}{W_x} [y F_z + (z + a) F_y]$
<p>Bending stresses in the x-z plane:</p> $\sigma'_{by} = f(M'_y) = \frac{1}{W_y} [x F_z + z F_x]$ $\sigma''_{by} = f(M''_y) = \frac{1}{W_y} [x F_z + (z + a) F_x]$
<p>Torsional stress:</p> $\tau = f(M_d) = \frac{1}{W_p} [x F_y + y F_x]$

Table 1: Stresses in the end element due to the force shown in Fig. 1

A = cross-sectional area;
 W_x, W_y, W_p = section moduli.

Theoretically, the first elements are better suited for strain-gage installations than the end elements, because more sensitivity is available at that position due to the greater torques. This would also avoid having to pass the leads over a moving axis. However, the transmission of the end element occurs through the first element, resulting in force and moment relationships on the first element that are difficult to measure. This means that measurements on the end element are to be preferred. Figure 1 shows the strain-gage arrangement on the end element on which a randomly selected force F is acting.

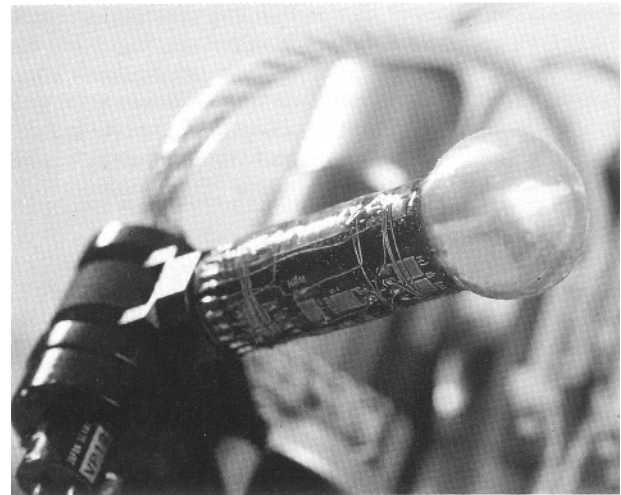


Fig. 2: Photograph of an end element with applied strain gages.

This force causes a longitudinal force N_z as well as bending moments about the x and y coordinates and torsion about the longitudinal axis of the element. Table 1 defines these stresses based on the designations given in Fig. 1. Figure 2 shows a photograph of an end element fitted with strain gages.

Mounting of the strain gages

The number of strain-gage bridge circuits used and their point of mounting were given by the six unknown quantities that were to be determined. These were the three force components F_x, F_y and F_z and the coordinates of the point of action for the resultant force. This requires six strain-gage bridge circuits. These must be mounted such that the equations that are produced are linear and independent. Figure 3 shows the arrangement of the strain gages on the four sides of the end element.

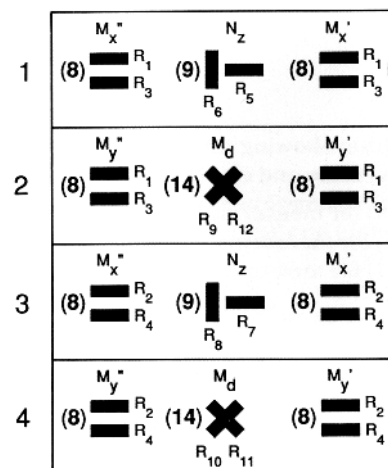


Fig. 3: Positions and measurement directions of strain gages applied to the end element of the gripper, displayed in the form of a development.

A schematic diagram illustrating the wiring of the separate strain gages in full bridges is given in Fig. 4. Figure 4a shows the strain-gage connections for measuring the torque and those for longitudinal force measurement are shown in Fig. 4b. Figure 4c illustrates the strain-gage arrangement for measuring the moment of torsion.

The bridge circuits (8) measure the bending moments M_b in the x-z and y-z planes. The bridge circuit (9) measures the normal force N_z in the z direction and circuit (14) measures the moment of torsion M_d . The strain-gage arrangement shown in Fig. 2 was selected such that the

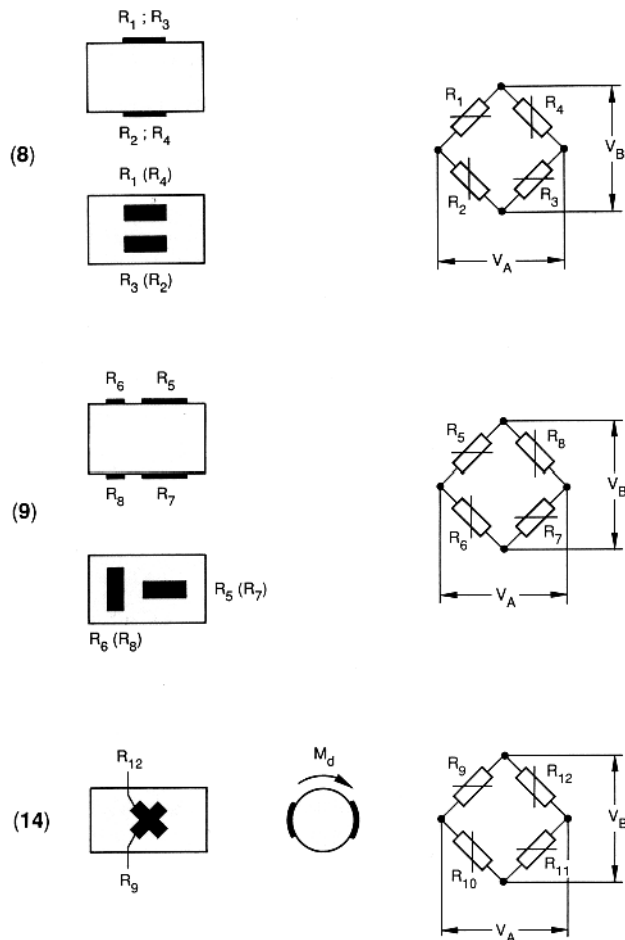


Fig. 4: Diagram showing the method of connecting the strain gages on the end elements into full bridges:

- a) circuits (8) for measuring bending moments,
- b) circuit (9) for measuring the longitudinal force,
- c) circuit (14) for measuring the torsional moment.

signals in the separate bridge circuits were only dependent on the load to be measured. Bridge (8) reacts only to bending loads, bridge (9) only measures the longitudinal force and circuit (14) only reacts to the moment of torsion. In addition, all three variants are independent of the temperature due to the temperature compensation in the full bridges. The assumption that each circuit only reacts to the relevant load is based on the ideal case

and is of only a theoretical nature. Slight deviations in the strain-gage positioning and the inhomogeneity of the material used cause unpredictable interference due to cross-talk which can however be measured. Correction characteristics can be derived from the results obtained and these are used as the initial quantities for a correction procedure. This correction method, termed decoupling, takes place in a software module developed by the ORS.

Control principles with special consideration to force control

In order to achieve a certain sequence of movement or a defined application of force during gripping, it is necessary to control both the velocity and the position of the finger gripper. The following design for the control structure of the gripper system was produced to keep the degree of complexity within limits:

- Position controller:

Comparison of the set and feedback values of the position together with linear position control (analog).

- Force controller:

Comparison of the set and feedback values of the force together with linear force control (digital) to which a two-point controller is wired in parallel as a multiplier; a position control is superimposed on the complete force control.

With the force control the production of defined forces gripping the object is assigned to a position controller.

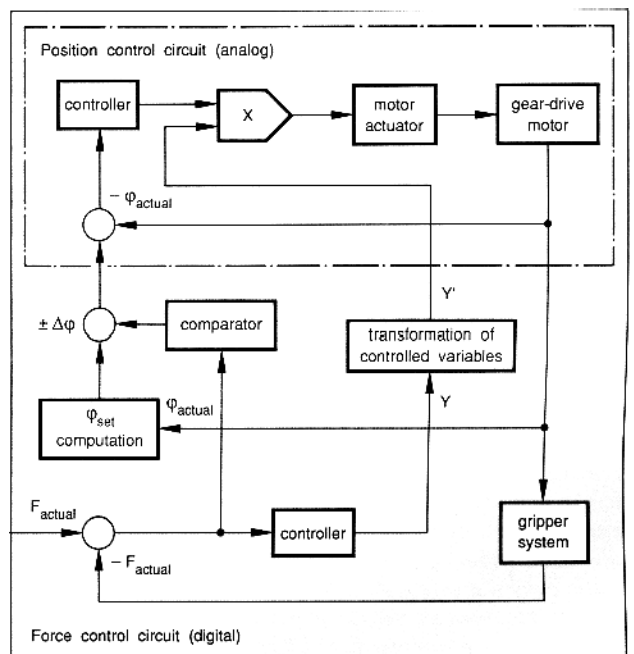


Fig. 5: Control flow diagram showing the force control principle: analog position control with a superimposed digital force control.

The force control principle used can therefore be interpreted as a digital force control with a superimposed analog position control. The signal flow of the controller is shown in Fig. 5 and can be described as follows:

At the moment of contact the current position of the gripper is retained. Simultaneously, the forces and moments (F_x , F_y , F_z , M_x , M_y , M_z) acting on the gripper system are determined, referred to an x , y , z coordinate system derived from the gripper's TCP (Tool Control Point), as shown in Fig. 6. From the signals representing the difference between the set and feedback values of the force components F_x and F_y the controlled quantities Y and X are obtained using the controller parameters for the drive of the gripper axes. To explain this better, Fig. 7 is a photograph of the gripper shown diagrammatically in Fig. 6.

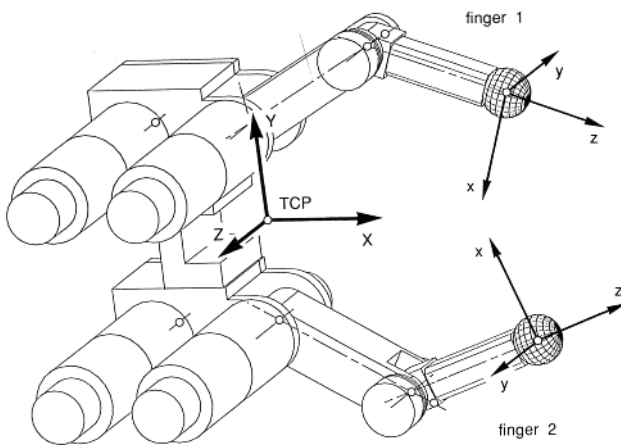


Fig. 6: Cartesian coordinate system derived from the gripper TCP; all forces and moments acting on the end elements are referred to this system.

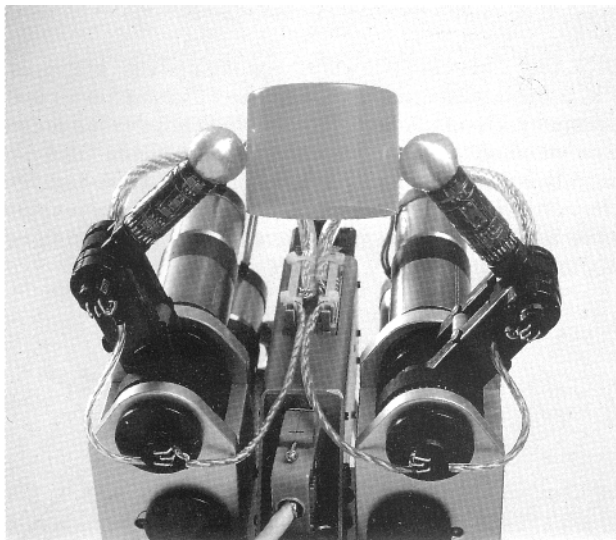


Fig. 7: Photograph of the arrangement shown diagrammatically in Fig. 6.

Apart from being dependent on the time and frequency, the transfer function between the motor voltage and the generated gripper force also depends significantly on the position and shape of the gripper system. This means that the controlled quantity must be regarded as an adoptive quantity depending on the geometrical shape. This fact is clearly explained in Fig. 8. Therefore, for example, the transfer characteristics between the motor voltage and F_y in the figure on the left is more flexible than in the figure on the right. This applies vice versa for the force F_x . The empirically derived adaptive control parameters take into account the different mechanical gripper system flexibilities which depend on the angular position. The signals for the controlled quantity which are computed in this way are passed directly to the velocity input on the multiplier in the position control circuit. The advantage of this kind of clocked digital force control compared to the linear digital force control is a sensitive and fast reaction to control deviations.

Basic gripper design principle

During the discussion at the beginning of the project, it was decided to use a two-finger gripper with four degrees of freedom. The experience gained on the project can however be easily transferred to the more elaborate version of the three-finger gripper with nine degrees of freedom. Since most components are made from aluminum and miniature DC motors are used, a low weight of 6.5 kg (14.3 lb) could be maintained. Figure 9 shows an overall view of the gripper.

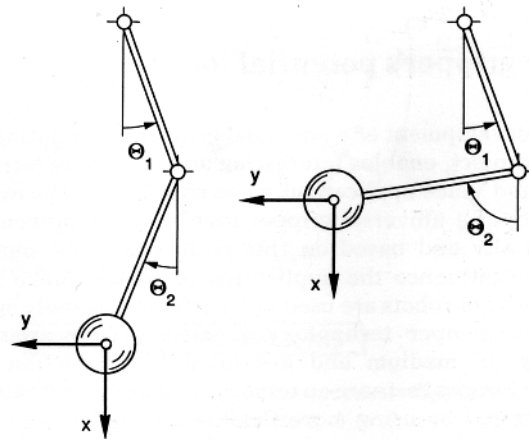


Fig. 8: Relationship of the motor-generated gripping force to the angular position of the end element.

Despite the high gear ratio the play in the system was kept low by the application of planetary gears and toothed belts. The motor for the first joint was mounted in the second element to satisfy the requirements for drive decoupling and to ensure that the finger was as slim as possible. This provided easy access to the objects to be manipulated in spite of the presence of the sensor elements. The voltage amplifiers for the strain-gage signals were located between the motors to keep interference effects due to the leads as low as possible.

Capabilities of the gripper system

Compared to conventional gripper systems some points are outlined below which particularly show the performance of OEDIPUS:

Force measurement system: Generally, the acquisition of forces and moments is made through indirect measurement of the motor current or through sensors mounted at the interface of the manipulator and gripper. Both methods have the disadvantage in that they are able to measure the internal or external forces either not at all or only inaccurately. The ORS gripper however determines the gripping forces with regard to size, direction and gripping point and therefore enables the determination of external and internal forces.

Optimum grip: By using the complex force measurement system and appropriate mathematical software, it becomes possible to detect and react to external forces and moment effects on the object during the gripping process.

Manipulatory capability: The ORS gripper does not suffer from the restrictions of conventional grippers. Gripping can take place symmetrically, asymmetrically or eccentrically. Also, the maximum width of grip has been extended significantly. The direction of movement during the opening and closing of the gripper can be varied within a certain range.

Programmability: OEDIPUS can be rapidly adapted to the most varied tasks by the application of different software programs.

The gripper's potential for use

The development of a universal gripper, culminating in this project, enables interesting and promising terrestrial and space applications to be considered. The availability of a universal gripper that has been proven industrially and based on this prototype could significantly influence the application of robots. Since the majority of robots are used in transfer or assembly operations, gripper technology assumes decisive significance. In medium and low quantity production rearrangement costs are an important factor which can be minimized by using more flexible systems. If, by just changing the software, the gripper is able to carry out new activities in a modified system environment, this would then be an important way of saving costs.

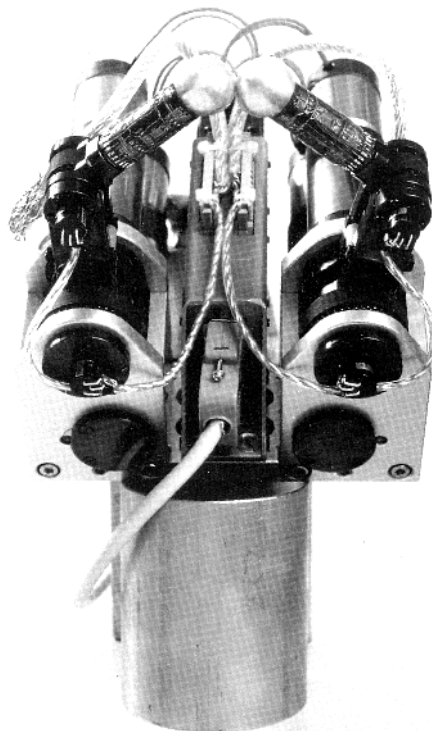


Fig. 9: Overall view of the gripper.

Similar concepts apply to space travel. Since the deployment of man in space is very expensive, great efforts are being made to support his activities or to even replace them in some instances. A gripper that can imitate the most important functions of the human hand is a step in this direction. Manipulatory tasks on experiments that are only supervised by man from time to time can be largely fulfilled by this type of gripper.

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