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MAINTENANCE OF SPACE VEHICLES IN ORBIT BY MEANS OF REMOTELY CONTROLLED MANIPULATORS -- A JOINT PROJECT BY ERNO, KYBERTRONIC, KLERA

H. Kleinwächter and W. Wienss

Translation of "Wartung von Raumfahrzeugen im Orbit mit Hilfe von ferngesteuerten Manipulatoren -- ein Gemeinschaftsprojekt der Erno, Kybertronic, Klera," Elektronik für Raumfahrt und Atomtechnik, Lörrach, West Germany, Report No. 72-098, Presented at the 5th Annual Meeting of the DGLR, Berlin, West Germany, October 1972, 9 pages

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16. Abstract Conventional tools are based on the manifold functions of the human hand. A more sophisticated tool, "Syntelmann" is used in outer space, the deep sea and radioactive areas. Controlled to the "exoskeleton" in turn attached to man, the "slave" follows the "master." Degrees of freedom are determined.

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"...for indeed, if every tool could check its performance on receipt of instructions or even anticipating orders, thus, if the shuttle could weave by itself and the zither pick could play by itself, then indeed the master craftsman would need no journeyman, and the masters would need no slaves." /2*

Dr. Xavier B. Ghali, who is engaged in preparations for the employment of industrial robots in Europe, placed these words by the Greek philospher Aristotle at the beginning of his report entitled "Robotology," in the Schweizer Maschinenmarkt, No. 13, 1972. These thoughts by Aristotle were pure utopia for his period of over 2000 years ago. Today, however, this old wish-dream of humanity has already been fulfilled in part, while in part it is in the process of single-minded realization.

Men conceived the machine in order to make work easier, to be able to perform it more efficiently, and to extend it over greater distances. The machine was created from observations of nature, often as an imitation of the human body. Thus, the club served Stone Age man as an extension of his arm, born by the wish to remove himself locally from the danger zone and to be able to deal harder blows than with the unarmed hand. Most of our tools, a subgroup of the machine, such as the shovel, the pliers, the wrench, and others have come into being as functional, specific copies of one of the many possible forms of the human hand. The greater efficacy, however, is opposed by the considerably greater versatility of the human hand. Constantly increasing

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

activity of man in an environment hostile to life, especially the new technology of atomic energy, of space travel, and deep-sea research, suggest the design of telemanipulators that can perform these activities in place of people.

At present, the Institute for Research and Development, Klera, in Lörrach, under contract with the Federal Ministry for Education and Science, Bonn, in collaboration with the Nuclear Assistance Mobile Unit of the Society for Nuclear Research in Karlsruhe and the French Research Center in Saclay, developed the anthropomorphic machine "Syntelmann," designed for the task of performing rescue, repair, and blocking operation in place of people endangered by radiation during accidents in nuclear plants. In order to replace people in as many work situations as possible, it must have a flexibility comparable to human arms and hands. This led to the design of a machine resembling a human being which had operating arms, telephoto eyes for the transmission of 3-D stereophotographs, power, temperature, and other remote sensors as well as a device for vehicular or two-legged locomotion which can be conveniently steered from any remote distance by a man called "master."

The name "Syntelmann" stands for the abbreviation for SYNchron-TELe-MANipulator. The system consists of a master and a slave. The slave is a machine with a shape resembling a human, and the master is the man who controls this machine from a distance. However, the controlling is not done by hand-operated levers and electric push buttons, as with the usual, simple, remotely controlled machines, but through a light-weight articulated-joint system, the exoskeleton buckled onto the limbs of the master. This is adapted to the body of a master in such a way that it moves parallel to the skeletal bone structure of the master in all movements. The movements of the master's exoskeleton are /3
converted into electric currents which are transmitted to the slave,

and they control electric motor and pneumatic muscles in such a manner that the limbs of the slave perform exactly the same movements as those of the master.

The most important information transmittal system is that of the two-eyed stereo television instrument. By means of two separate television channels, the pictures of the left and right television camera are transmitted separately to the left and right eye of the master. For this purpose, two separate television pickup devices can be used that are observed through a semitransparent mirror by means of two pairs of polarization filters. Thus, the 3-D impression of the manipulation area is formed in the brain of the master. Additional information regarding the field of operation is received by the master by way of force effect, roughness, humidity, radioactive radiation, sensors, and others built into the hands of the slave.

Wire strain gauges used as force sensors measure the reaction forces at the engaged machine hand and bring them into a relationship with the corresponding forces of the master's hand in the exoskeleton. By this means, the master is in a position to apply pre-defined forces to the object to be grasped. The lever system is strong enough to transmit a gripper force of 550 newtons. On the other hand, the slight deflection of these levers and a gripper force of .5 newtons, as used when gripping a chicken eggshell, is sufficient to modulate the force control circuit. Thus, it is possible to definitely control well-defined forces in the .5 to 400 newton range with the same hand pincers.

Man differs anatomically from the other less-developed forms of life not only through a much more efficient brain, but also through his exceedingly versatile hand. Nature has endowed the upper human extremity with an extravagantly large number of movements. Each arm consists of 30 bones more or less flexibly

interconnected, of which 27 are in the hand. For determining the minimum number of joints of a machine arm, it is necessary to know the smallest number of movements that are independent of each other -- called degrees of freedom -- but ensure any 3-D position of the hand torso consisting of a pincer. There are at least seven degrees of freedom. Because of the general position of the body of a hand, it is necessary to have settings for height, width, and depth of its center of gravity and, in addition, its angle of yaw, pitch, and roll. To this is added at least one pincer-shaped thumb-finger substitute which requires the seventh degree of freedom. However, in imitation of nature, in the future, machine hands or terminal effectors with more than one degree of freedom will be employed so that the number of hand members will represent a functional maximum. The joints of this anthropomorphic so built are driven by low-inertia, nonferric DC disc rotor motors built by BBC for which drives with large reduction ratios and high efficiency are required. To this end, for Syntelmann, the harmonic drive gear unit of the US-Shoemaker Company, and our own developments were employed. The harmonic drive gear unit combines the following advantages: small weight, small volume, gear ratios of more than 1:200 in a single stage with a high starting torque and an efficiency of over 50% with a small angular play of less than 5 min of arc. Position control is effected by means of a comparison between design and actual values of potentiometers with unlimited resolution. The drive motors are controlled by way of variable-gain amplifiers with triac circuit based on the phase-shifting principle. To improve the hunting behavior, a velocity dependent feedback is employed.
The tachogenerator required for this purpose is eliminated by /4
means of scanning the motor emf during current intervals and by electrically differentiating the value of the position potentiometer. This resulted in an exceedingly small electronic component for the 14 150-W amplifiers of both arms.

At Klera, there are at present two novel gear motors under development that have many advantages over classical designs. Fig. 6 shows a diagrammatic sketch of a sinusoidal electromagnetic disk drive. Using a paired single-pole rotary magnetic field, the variable-gear circular disk (4) is made to engage with a fixed bevel gear (6) at two diametrically opposed points of its circumference which has two teeth less than the circular disk (4). That way, it turns with great torque and no backlash by using only two teeth relative to the fixed bevel gear (6) for one full revolution of the rotating magnetic field. In this manner, a reduction ratio of several hundred can be attained with only one pair of gears. The solid current connections of the synch field system (2) are also more advantageous than the DC collector motors used up to now.

Fig. 7 shows the variant of a fluidic motor functioning on the same principle, where the rotating axial deformation wave of disk flexspline (18) is generated by at least two diametrically located elastic expansion chambers (22) being sequentially inflated by pressurized gas or by hydraulic fluid. By using fluids with a suitable boiling point, circulating in a hermetically closed cycle, such a system with an evaporator and a condenser can be operated directly by solar energy, for instance for application in space vehicles. With an open control system, both units can also be utilized as digitally controllable stepping motors.

Of advantage for the efficient design and reliable operation of telemanipulators in atomic and marine engineering as well as in the vacuum of space are also the hermetically sealed universal joint capsules that are being developed by us. As can be seen in Fig. 8, each telemanipulator arm can easily be structurally assembled solely from independent universal joint capsules.

Each capsule contains a drive motor (11), a greatly stepped-down drive unit (5) as well as angular sensor (16), torque, and temperature sensors. Topologically, the angular sensor is connected to a rotary system through a hollow axle (15). All current conductors and air conduits are fed through this hollow axle, obviating all link coupling loops susceptible to trouble. Due to the limited angle of twist between the two articulated arms (9), elastically extensible or elastically foldable metal bellow seals (10) can hermetically seal off the interior space of the manipulator arms from the surrounding vacuum of space.

At the 1972 Hannover Fair, a two-legged robot was exhibited whose 12 joints had already been manufactured in the form of independent universal joint capsules. Under contract with ESRO [European Space Research Organization] last year -- jointly with the ERNO and the Kybertronic -- a conceptual study had been worked out according to which, in the next eight years, a special satellite equipped with Syntelmann arms and television eyes will be permitted to maintain and to repair (from earth at regular intervals) the many news and research satellites, the total value of which, until 1995, has been estimated to be more than $2 billion, thereby extending the useful life of these valuable instruments.

In accordance with the ESTEC conceptual study, Contract No. 1436-71 EL, a teleoperator space vehicle has been planned which, with its six extremities and its pair of television eyes, might be called Schiwa, based on the Brahman multi-armed deity (title page). Schiwa is an unmanned teleoperator system that can be remotely controlled from a command station. This command station can be located either on earth or in a manned missile -- such /5
as TUG or SHUTTLE. For a diameter of 2.4 m and a weight of 600 kg, it shall have, aside from the usual motor, flight attitude and microwave signal transmission systems, an anthropomorphic pair of operator arms as well as a third, oversized, long,

active docking arm, the terminal effector of which grasps the satellite to be serviced at as low a relative speed as possible and can, if necessary, "despin" it. Then, by means of the two active operating arms, three unpowered, passive telescope arms are to be locked into position on the satellite, in order to be able to carry out the necessary maintenance work. Due to the limited propagation rate of the microwave signals, at larger distances between the command post and the Schiwa, technical control difficulties developed. These can be overcome by either curtailing the maximum manipulation velocity -- for instance through iterative remote control or, according to H. von Muldau, by means of "hierarchically organized cybernetics" machine intelligence.

The following film development represents the Syntelmann described herein at different stages as well as the mechanical function of a reduced-scale Schiwa model.

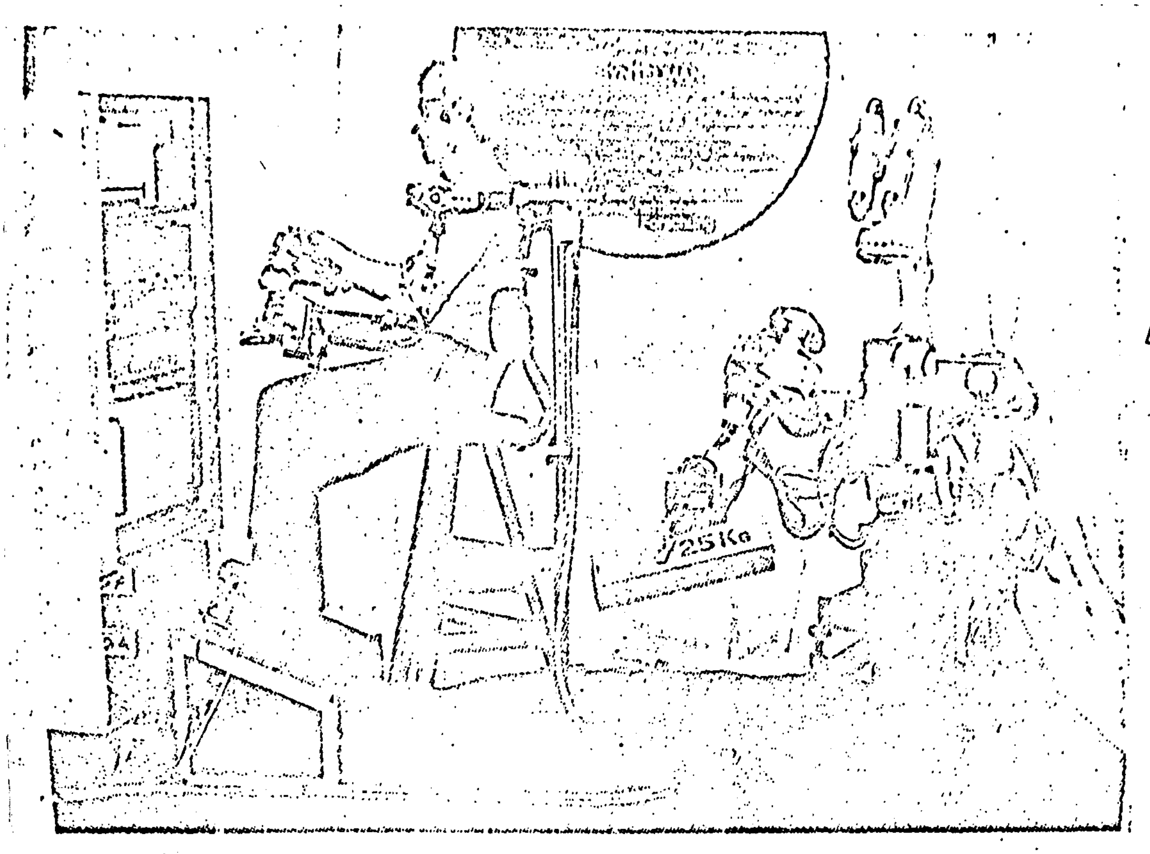


Fig. 1

Electronics
for
Space Travel
and Atomic Engineering

Kleinwächter
D·7850 Lörrach Kreuzstrasse 105

[Translator's note: This imprimatur appears on all figures.]

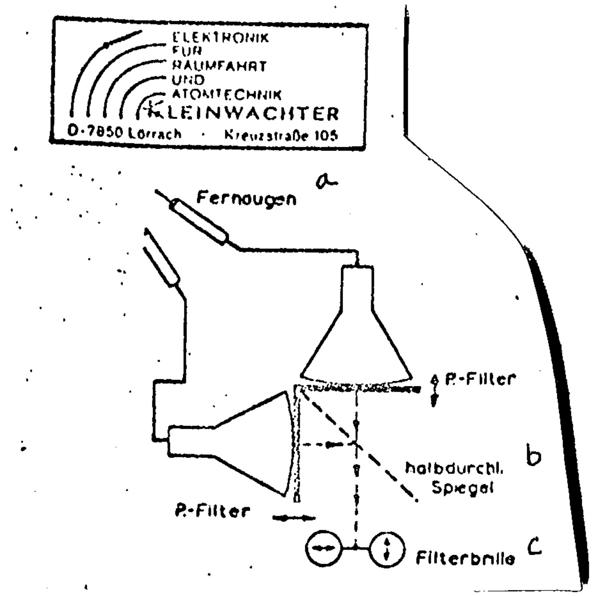


Fig. 2. Syntelmann. Stereo television transmission.

Key: a. Television eyes
b. Semitransparent mirror
c. Filter spectacles

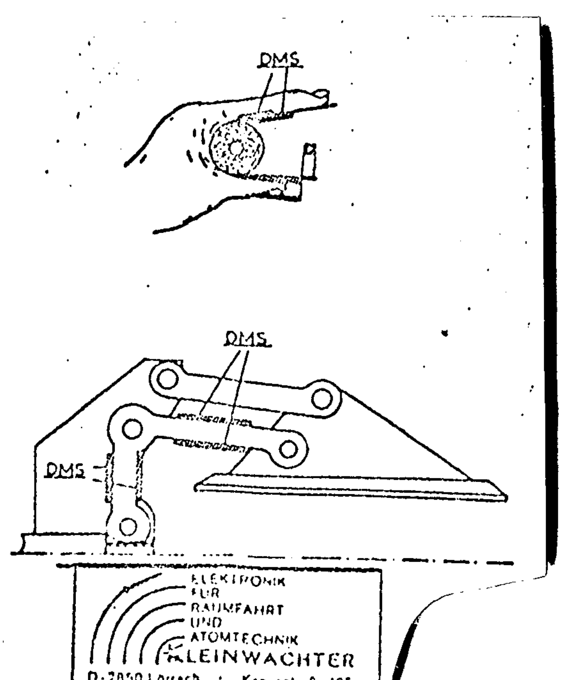
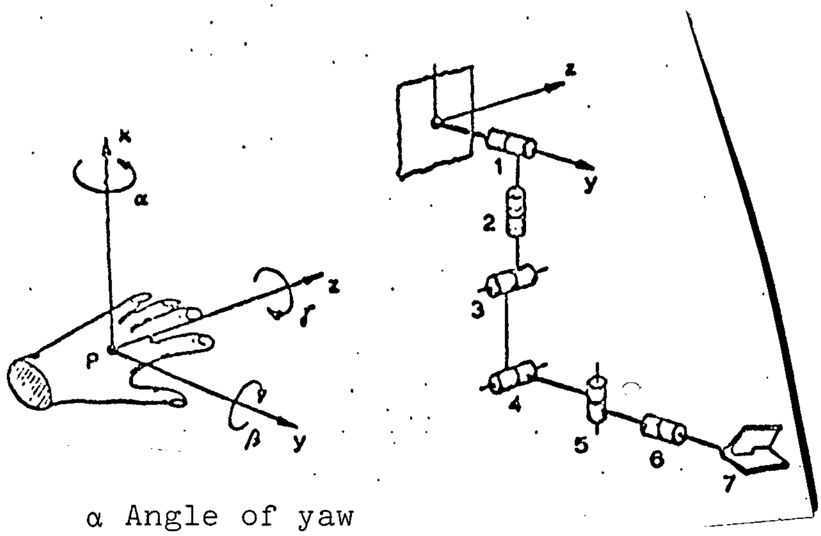


Fig. 3. Master and slave hand pincers.

Key: DMS = Strain gauge



x Height α Angle of yaw
y Width β Angle of pitch
z Length γ Angle of roll

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Fig. 4. Degrees of freedom.

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FIG. 5

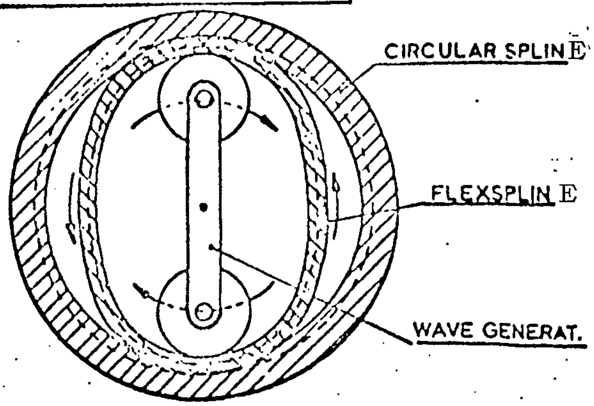

Fig. 5. Harmonic-drive gear unit. Basic elements.

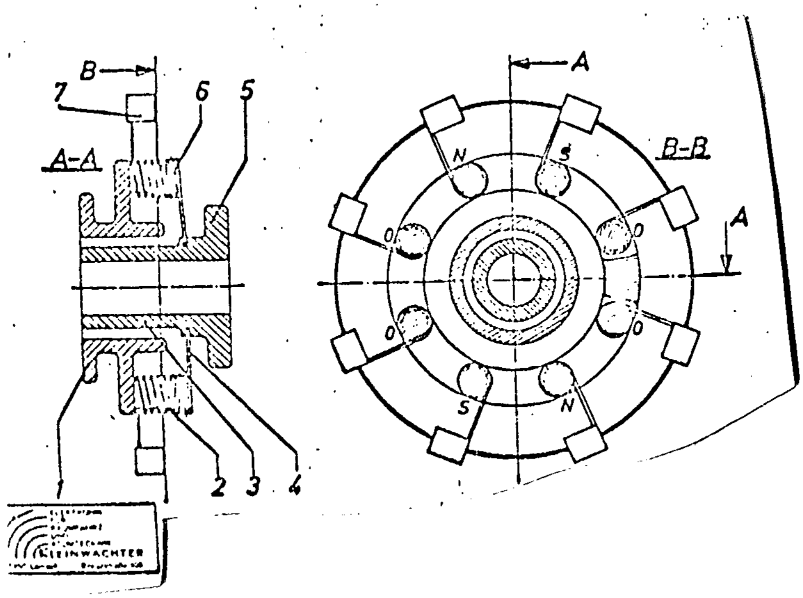

Fig. 6. Electromagnetic-disk sinusoidal motor.
Patent no. P 22 36 159.7

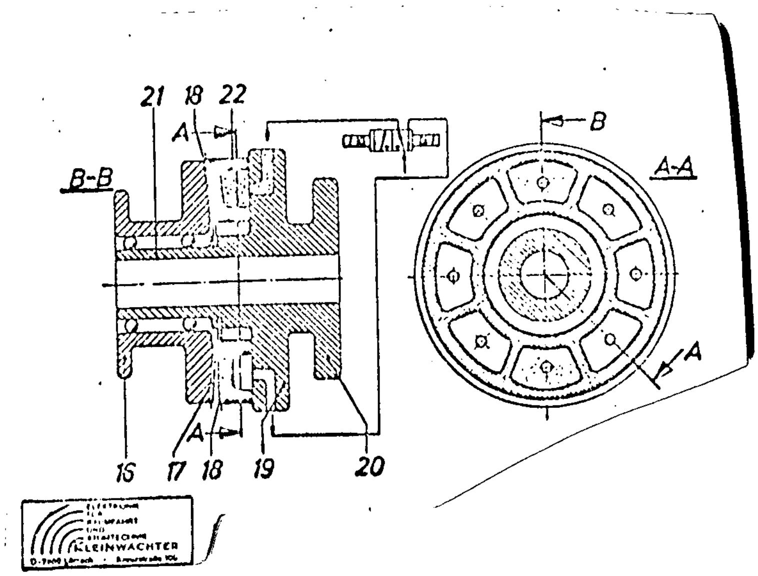

Fig. 7. Fluidic disk sinusoidal drive motor.
Patent No. P 22 36 159.7

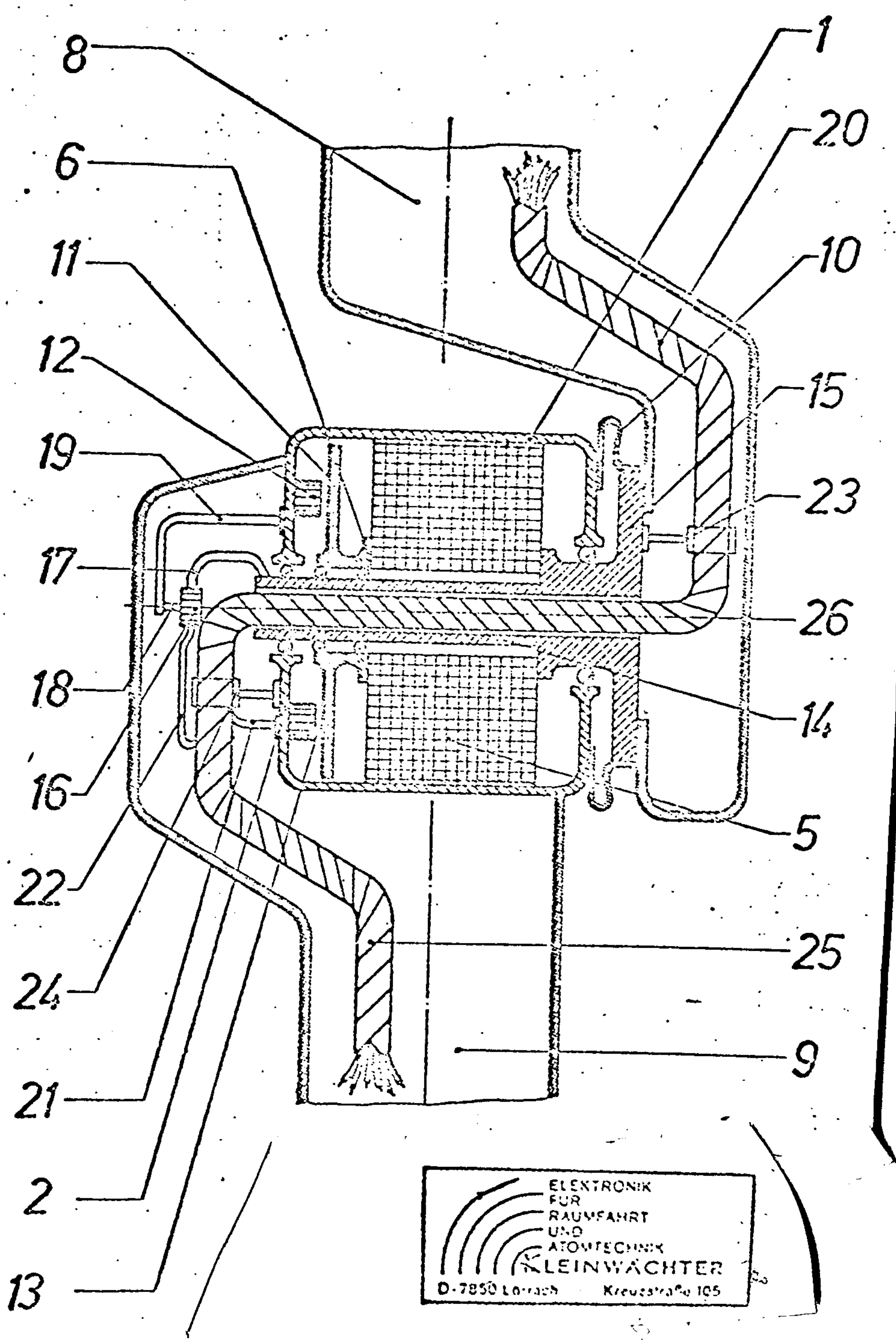

Fig. 8. Hermetically sealed universal joint capsule
Patent No. P 22 28 598.9

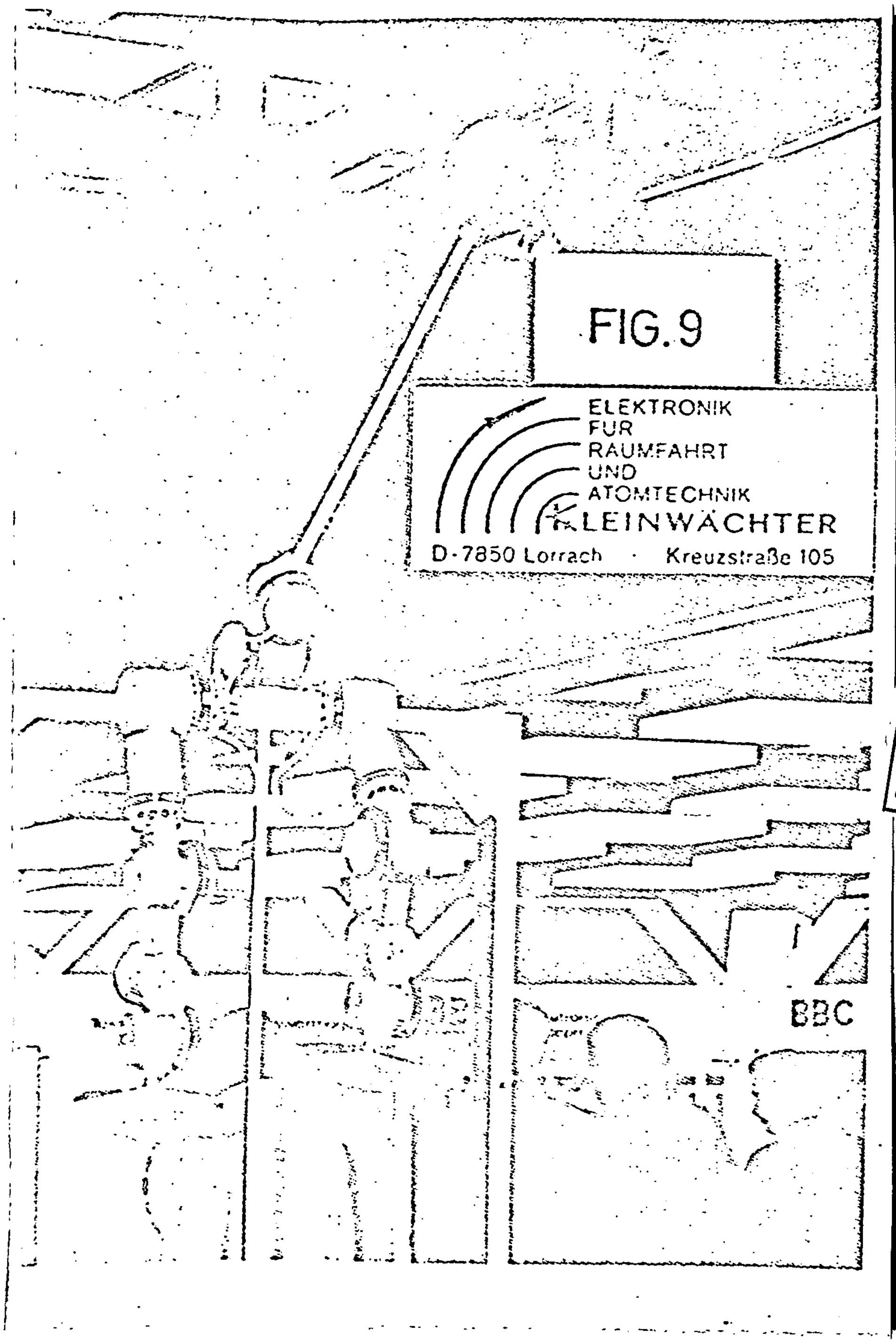

Fig. 9. Syntelmann locking mechanism.
Hannover Fair, April 1972.

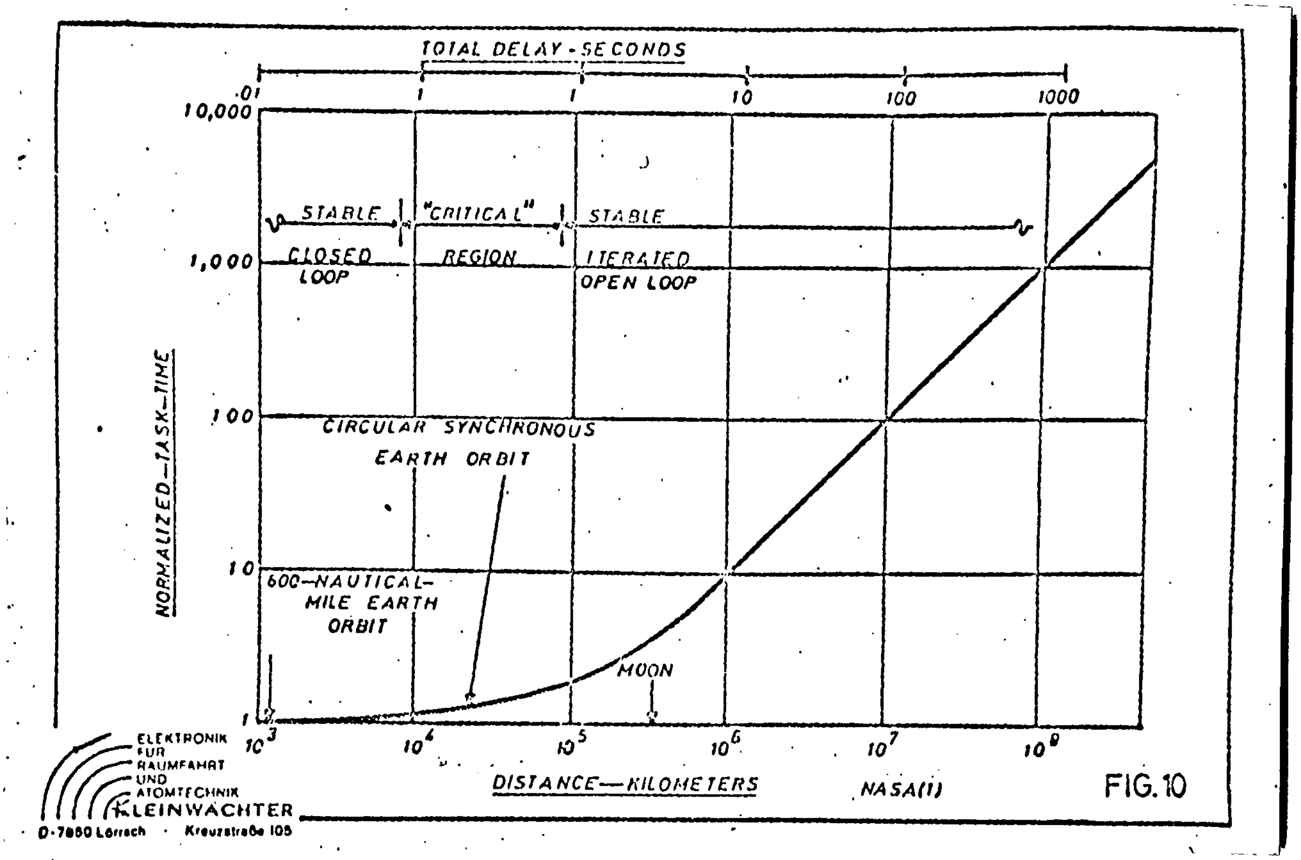
TOTAL DELAY - SECONDS
.01
1
1
10
100
1000
10,000
1,000
100
10
1
STABLE
"CRITICAL"
STABLE
CLOSED LOOP
REGION
ITERATED OPEN LOOP
NORMALIZED—TASK—TIME
CIRCULAR SYNCHRONOUS EARTH ORBIT
600—NAUTICAL-MILE EARTH ORBIT
MOON
10^3
10^4
10^5
10^6
10^7
10^8
DISTANCE—KILOMETERS
NASA(1)
FIG.10
ELEKTRONIK FUR RAUMFAHRT UND ATOMTECHNIK
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Fig. 10.

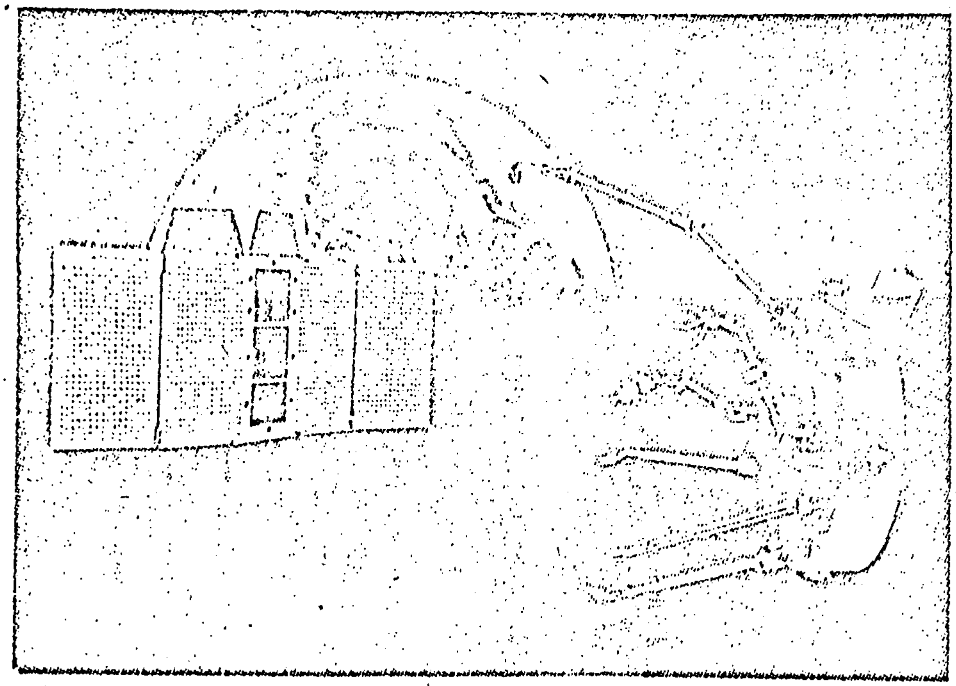

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Fig. 11. "Schiwa" approaches the TD satellite.

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