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Robot Design for a Vacuum Environment

S. Belinski, W. Trento, R. Imani-Shikhabadi, and S. Hackwood
University of California, Santa Barbara
Santa Barbara, CA 93116

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1. Abstract

The cleanliness requirements for many processing and manufacturing tasks are becoming ever stricter, resulting in a greater interest in the vacuum environment. We discuss the importance of this special environment, and the developement of robots which are physically and functionally suited to vacuum processing tasks. Work is in progress at the Center for Robotic Systems in Microelectronics (CRSM††) to provide a robot for the manufacture of a revolutionary new gyroscope in high vacuum. The need for vacuum in this and other processes is discussed as well as the requirements for a vacuum-compatible robot. Finally, we present details on work done at the CRSM to modify an existing clean-room compatible robot for use at high vacuum.

2. Introduction

Among the many advantages of robots is their ability to work in harsh environments. Robots are being developed for maintenance of nuclear facilities (for example, the ODEX walking robots by Odetics, Inc) and for high temperature and other harsh environments. The high vacuum environment is now becoming more important in many high technology manufacturing tasks, and as a result the need for vacuum compatible robots is increasing.

Most processes requiring high cleanliness standards are now performed in clean rooms. The principal users of clean rooms are advanced industries making use of thin film technology. Materials manufactured in ultraclean environments include [1]: VLSI semiconductors, compact discs, photographic films, magnetic and video tapes, precision mechanisms and sterile drugs and antibiotics. Today's rigorous cleanliness requirements can be illustrated dramatically with the example of the actual development going on in the VLSI semiconductor field. Table 1 shows that the critical particle diameter, i.e. the maximum size of tolerable contaminant particles, is projected to be $0.05 \, \mu m$ in the near future.

Storage density (kbit/chip)	Line spacing on wafer (μm)	Minimum critical particle diameter (μm)	Market dominance period
16	4.0	0.4	1981 - 1984
64	2.5	0.3	1984 - 1988
256	1.5	0.17	1984 - 1988
1×10^3	0.9	0.09	1988 - 1990+
4×10^3	0.5	0.05	1988 - 1990+

Table 1. Line spacing and critical particle diameters for high density integrated circuits (adapted from [1]).

As of 1985, the most demanding air cleanliness level established in the U.S. Federal Standard 209b is a cleanliness class 100. This refers to a maximum concentration of $100/ft^3$ for

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* Research Assistant in the Department of Mechanical Engineering, UCSB
† Faculty in the Department of Electrical and Computer Engineering, UCSB
†† The CRSM is one of the Engineering Research Centers established by the National Science Foundation

particles of diameter greater than or equal to 0.5 μm. It is proposed in [1] that the present standards be extrapolated as listed in table 2.

Cleanliness class	Particles per ft³ equal to and greater than:			
	0.02 μm	0.1 μm	0.5 μm	5 μm
1	10^3	3 x 10	•	•
10	10^3	3 x 10^2	10	•
100	†	3 x 10^3	10^2	•
1000	†	†	10^3	7 x 10^0
10,000	†	†	10^4	7 x 10
100,000	†	†	10^5	7 x 10^2

* Indication not meaningful for statistical reasons.
† Indication not relevant for the definition of cleanliness requirements.

Table 2. Proposal for extrapolating the US Federal cleanliness standards (from [1]).

In the near future, cleanliness class 1 and even stricter environments will be required. The three main sources of particle contamination are: the outside air (10^7 - 10^8 particles > 0.5 μm m^{-3}), equipment, and humans, who give off about 100,000 dust particles > 0.3 μm and more than 1000 bacteria and spores per minute. An increasing number of specially designed robots are being used in clean rooms not only because of their potential efficiency and productivity, but also to replace one of the principal sources of contamination: human beings.

Eventually, a wide range of processing and analysis tasks will be performed in vacuum environments. The reasons for using this special environment are many and include the following [2]:

- To prevent physical or chemical reactions occurring between atmospheric gases and a desired process;
- To disturb an equilibrium condition that exists at room temperature so that absorbed gases or volatile liquids can be removed from the bulk of the material (e.g., degassing of oils and freeze drying), and adsorbed gases from the surface;
- To increase the distance that gas and vapor particles must travel before colliding with one another so that a process particle can reach a solid surface without making a collision (e.g., vacuum coating and the production of high-energy particles);
- To reduce both the number of molecular impacts per second and the contamination times of surfaces prepared in vacuo (e.g., clean surface studies and the preparation of thin films), and
- To reduce the concentration of a component gas below a critical level (e.g., the removal of oxygen, water vapor and hydrocarbons in tungsten filament valves).

Presently, epitaxial growth of semiconductor films takes place in the low vacuum range. Sputtering, plasma etching, plasma deposition, and low-pressure chemical vapor deposition are performed in the medium vacuum range. Pressures in the high vacuum range are required for most thin-film preparation, electron microscopy, mass spectroscopy, crystal growth, x-ray and electron beam lithography, molecular beam epitaxy, and the production of cathode ray and other vacuum tubes. [3] These environments are completely unsuitable for the presence of human beings. The special suits that are worn in outer space, for example, would be much less

appropriate in a specialized vacuum chamber used for a critical processing task. The amount of time needed to produce the desired pressure level once the suited worker had entered the chamber would prove to be quite long. The need for robotics and automated systems inside the vacuum chamber may thus be more urgent than in a normal environment or clean room. A principal advantage would be the ability to manipulate objects within the chamber without opening the vessel and subsequently re-evacuating, thus avoiding a very time consuming process. The availability of vacuum-compatible robots will improve the efficiency of many processes now carried out in vacuum and should encourage the use of vacuum processing in new areas.

There are a number of differences between the vacuum environment of space and that produced artificially on earth. Pressures can be achieved in vacuum chambers which are comparable to those in standard space orbits. Pressure levels reach 10^{-6} and 10^{-9} Torr at 200 and 800 km above sea level, respectively. However, in vacuum chambers on earth, the outgassing from components in the chamber works directly against the pumping equipment. In space there is no problem maintaining the pressure, but it is known that the outgassing of the space vehicle causes an expanding gas cloud to surround it. The shape of this depends on the venting paths of the hardware, the outgassing of external surfaces and backscattering by the local atmosphere. Thus, outgassing is also a major concern in space. In addition, spacecraft are exposed to the full solar spectrum as opposed to only a fraction of the spectrum on earth. Possibly the most important difference between vacuum processing facilities on earth and those in space is the difference in the gravitational force. Some processing tasks may be better suited to the weightless environment of space.

3. APPLICATION: Gyroscope Assembly in High Vacuum

Delco Systems Operations in Santa Babara, CA has developed a revolutionary new gyroscope, which is now entering the production stage. For reasons described later, the assembly must take place in a high vacuum environment of 10^{-8} Torr. The CRSM is modifying an existing robot so that it can operate at high vacuum. It will be used by Delco for production of the new gyroscope.

Gyroscope Description
The gyroscope to be assembled is the hemispherical resonator gyro (HRG) which Delco has been developing since 1975. The HRG is not a laser based gyro, yet does not have the rotating parts usually found in mechanical gyroscopes. Edward Loper and David Lynch of Delco list the following attractive characteristics of this gyroscope[4]:

- Extremely low power dissipation, and hence negligible warm-up transient
- Passive mechanical integration of angular rate, but with whole angle readout, making it immune to electrical power interruption, and thus giving it high tolerance to nuclear radiation effects
- Ability to operate at very high angular rates without performance degradation
- Capability to operate over the military temperature range without temperature control.

The HRG consists of three principal parts constructed of fused quartz as shown in Figure 1.
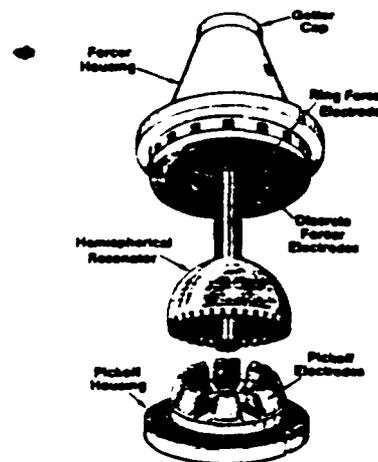

Figure 1. Principal Components of the HRG (from [4]).

These parts are bonded together with indium after being positioned relative to each other with accuracies in the sub-micron range. The principle that the gyro operates under was first described by G.H. Bryan, who did experiments on the vibrational modes of shells of revolution using wine glasses in the late 19th century. The basic operation of the HRG is represented in Figure 2. The "wine glass" in this case is the hemispherical part of the resonator, which is forced to vibrate at 2500 Hz, resulting in a standing wave with a zero-to-peak flexing amplitude of 4μm as indicated in Figure 2. As the entire gyro (all parts are fixed relative to each other) is rotated through an angle, the vibration pattern responds by precessing relative to the resonator through an angle proportional to the resonator's rotation angle. The location of the vibration pattern is sensed by electrodes located in the pickoff housing. By determining the movement of the vibration pattern relative to the case, and knowing the relationship between pattern movement and case rotation, the angle of rotation of the case is found. More technical details and test results may be found in [4], [5] and [6].

Need for a Vacuum Environment
The main components of the gyroscope are constructed of fused quartz, which is an inert, stable material having low thermal sensitivity and extremely low damping. This makes it an attractive material to use in precision mechanical and optical devices. It also exhibits extremely low internal damping, the damping time constant of the resonator being around 900 seconds. This means that very little energy is needed to sustain the vibration and that a power failure will not cause a loss of positional information until approximately 15 minutes have passed. The positive aspects of using fused quartz will deteriorate as the quartz becomes less pure. Even gases which attach themselves to the surface of the HRG components will cause variations from optimal gyroscope performance. The gyroscope thus must be manufactured in a high-vacuum environment and maintained at such throughout its life, a minimum of 20 years.

Gyroscope Production
In order to achieve a relatively high production rate for the gyro, Delco has proposed the use of a large vacuum chamber as shown in Figure 3. There will be a large central chamber surrounded by 12 smaller compartments, each of which may be opened to either the outside or the central chamber. The central chamber will be constantly maintained at high vacuum. Ideally, then, the raw gyro parts would be placed into compartment #1 and be removed sometime later as a completed gyro, with the intervening assembly tasks performed automatically. One alternative to this is a smaller vacuum chamber in which all steps of the assembly would be performed. This would result in an extremely slow assembly task due to the continual and time-consuming actions of venting and re-evacuating the chamber. In order to
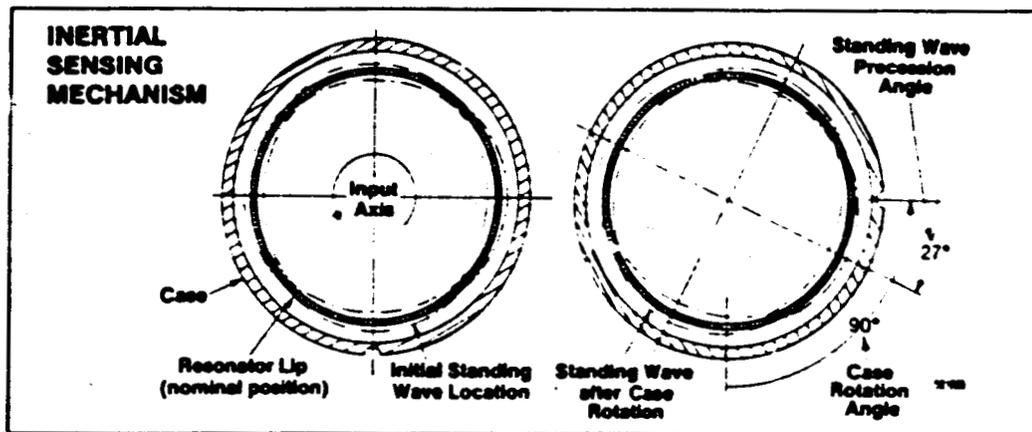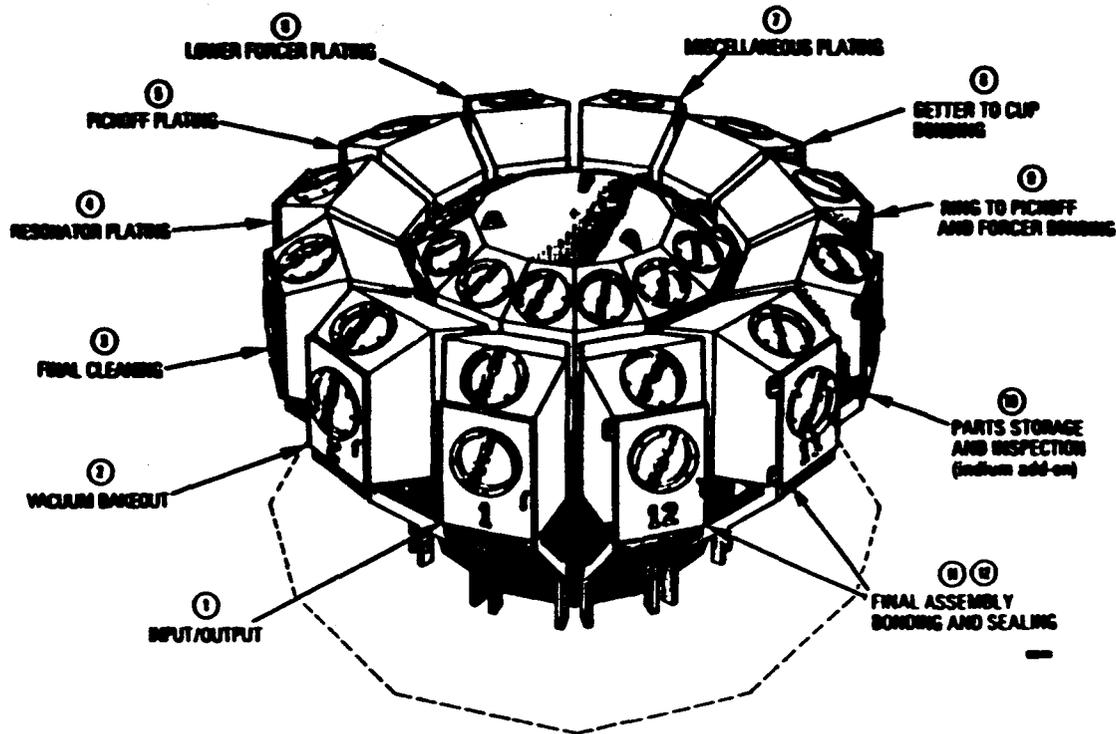

Figure 2. Inertial Sensing Mechanism of the HRG

Figure 3. Vacuum Chamber concept for HRG Assembly

take advantage of the increased manufacturing efficiency the larger assembly chamber would bring, a means of transferring gyro parts between various stages of assembly is required. A robot positioned at the center of the assembly chamber is the ideal component.

The availability of vacuum-compatible robots is presently limited, although this is likely to change in the near future. A prototype vacuum-compatible robot has been developed by Yaskawa of Japan, but the small size of this robot eliminates it from consideration for use in the Delco system. As research progresses on the development of vacuum-compatible robots, Delco has decided to have the CRSM modify an existing robot for use in their assembly task. The motivating factors in this decision were *cost* and *time*. Although it is desirable to obtain a robot which was designed and built specifically for the vacuum environment, the first step is to obtain a vacuum-compatible robot. This will occur more rapidly by doing a modification to an existing robot. When a 'ground-up' vacuum-compatible robot becomes available it can then be compared to the modified robot.

4. Description of the GMF E-310 Clean-Room Robot

The robot undergoing modification at the CRSM is a GMF (General Motors - Fanuc) model E-310 cylindrical coordinate robot, originally designed for use in clean rooms to class 10. This robot was chosen for its size and configuration as well as its good accuracy and repeatability for a robot of its size. Tests at the CRSM have shown the repeatability to be ±10μm. The E-310 used for the gyroscope assembly task has four degrees of freedom (see Figure 4) consisting of two linear axes and two rotational axes. The robot has three main housings which are joined by the shafts of two linear axes. The base housing contains the motors for the Z-axis and the Theta-axis. The Z-axis motor, through a belt, drives a lead screw - linear bearing - linear guide assembly which causes the Z-axis shaft to move vertically. An electromagnetic brake is installed on the top end of the lead screw to prevent the robot from dropping when power is not available. The Theta-axis motor is linked to the robot base through an RV gear reducer and a pair of spur gears. A cross roller bearing is used to support the robot

99

and allow for rotation. The R-axis housing sits atop the Z-axis shaft and contains a mechanical configuration very similar to that of the Z-axis. A motor mounted in the housing is coupled to the horizontal R-axis shaft through a lead screw, driving it back and forth. At the end of this shaft is the wrist housing, containing a fourth motor which drives the end-effector mounting plate (Alpha-axis) via a right angle gear set.
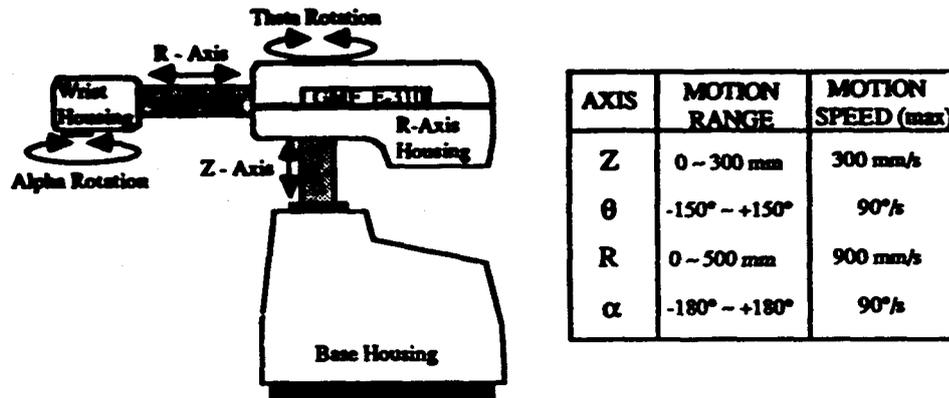
AXIS	MOTION RANGE	MOTION SPEED (max)
Z	0 ~ 300 mm	300 mm/s
θ	-150° ~ +150°	90°/s
R	0 ~ 500 mm	900 mm/s
α	-180° ~ +180°	90°/s

Figure 4. GMF E-310 Robot configuration and specifications.

The task for the researchers at the CRSM was then to modify the GMF E-310 so that it not only could operate in a vacuum environment to 10^{-8} Torr, but could also operate over long time periods without degrading its surroundings (outgassing, etc). The design requirements called for a modified robot with capabilities as close as possible to the original robot. The motion range of the two rotational axes would definitely be needed for the assembly task in the vacuum chamber. As for the linear axes, it was felt that their travel range could be restricted if necessary. The dimensions of the final vacuum assembly chamber had not been finalized at the beginning of the project, and could be adjusted based on the final specifications of the modified robot. It was expected that the final assembly chamber would not require the full 300mm of Z-Axis stroke. The stroke of the R-Axis would be related to the horizontal depth of the vacuum sub-chambers surrounding the main chamber. The robot must have enough horizontal stroke to reach into these chambers and perform specific functions. This is also dependent upon the final configuration of the end-effector, which might also extend into the chamber. It was agreed that an R-Axis stroke of at least 300mm would be desirable. An important point, however, is that this stroke must be *useful* when the robot is configured in the vacuum chamber. In other words, when the robot rotates inside the chamber, the wrist should just clear the inner wall. Then when the R-axis is extended, the wrist will move into the compartment with full stroke capability.

The completed robot must be capable of operating in temperatures as high as 100°C. Although some of the compartments will reach temperatures much higher than this, the central chamber will not. An initial bakeout may raise the temperature of the robot to two or three times its maximum operating temperature. This bakeout need not be accomplished in a matter of hours since the robot will remain in a vacuum atmosphere as long as equipment service intervals will allow. A degassing cycle as long as one to three days is thus acceptable.

In summary, the principal design requirements for the modification of the GMF E-310 robot for vacuum compatibility were:

- Modification of axes movement range:
  - Z-axis: maintain 300mm stroke if possible

100

- R-axis: maintain 500mm stroke if possible; if reduced, resulting stroke must be *useful* in the vacuum chamber
- Theta-axis: maintain ±150° rotation
- Alpha-axis: maintain ±150° rotation
- Limit negative effects on the vacuum environment (outgassing, etc)
- Design for ≤ 100°C operating environment
- Complete the modifications within one year.

5. Modifications for a Vacuum-Compatible Robot

The design of robots for vacuum brings together many disciplines, including the study of kinematics, dynamics, control, sensors, mechanics, materials, and tribology. Tribology, the study of friction, wear and the application of lubricants, is critical when applied to vacuum-compatible robots. Traditional lubricants have vapor pressures which are much too high for vacuum applications, resulting in rapid evaporation and unprotected surfaces. Dry lubricants, especially MoS_2, have been used in many high vacuum applications, however they tend to generate more debris and need replenishing more often than wet lubricants. Advances in both dry and wet lubricants are being made rapidly, helping to make this important part of the robot design less complex.

The first decision in the modification of the GMF E-310 was between two basic philosophies. The robot could either be totally exposed to the vacuum environment or it could be sealed in a type of "suit" which would allow the inside components to operate at atmospheric pressure, as they were originally designed to do. In order to expose the entire robot to a pressure of 10^{-8} Torr, a number of key changes would have to be made. The major ones would be in the lubrication systems, the surface finish and materials, and the motors. After examining this choice, it was concluded that it would entail a substantial amount of redesign work, and that a total exposure robot would be better designed from scratch. The goal then became one of designing a new housing for the robot which would seal it from the vacuum environment, while accomplishing the design goals as set forth in section 4. The sealing "suit" has to be as leaktight as the walls of a high-quality vacuum chamber, yet must also allow the desired movement by sealing two linear (R and Z) and two rotary (Theta and Alpha) motions.

Rotary Sealing

A differentially pumped 360° rotatable platform from Thermionics was chosen as the rotational sealing mechanism. As shown in the cross section of figure 5(a), the platform contains three spring loaded seals which are 80% teflon and 20% graphite. Two chambers are formed which are pumped to different levels of vacuum. For this application, the chamber closest to the atmospheric pressure side is roughed to approximately 10^{-3} Torr, while the chamber closest to the vacuum side is maintained below 10^{-8} Torr using an ion pump. Figure 6 indicates the placement of the rotatable platforms in the design.
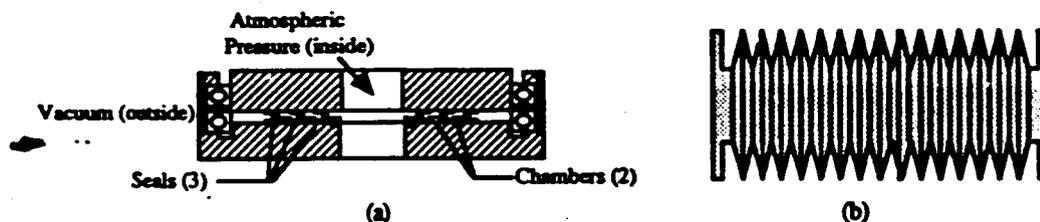

Figure 5. (a) Differentially pumped rotatable platform for sealing Theta and Alpha rotations, (b) Stainless steel bellow for sealing R and Z linear motions.

Linear Sealing

The two linear axes are sealed with vacuum compatible stainless steel bellows (figure 5b). Figure 6 shows how they are configured on the modified robot. Note that an additional bellow has been added to the rear of the R-axis housing. Because the robot internal pressure is essentially 760 Torr above its external environment, large forces exist which tend to push the R-axis forward and the Z-axis upward. For the bellow sizes which were chosen, the upward force due to the pressure differential is 477 lbs and the outward force on the R-axis would be 232 lbs if no compensation were used. The rear bellow shown in figure 6 surrounds a pipe which is attached to the same linear bearing as the R-axis. Thus, a force is produced which directly counteracts the one tending to force the R-axis outward. As for the Z-axis, the weight of the upper components tends to counteract the upward force sufficiently.
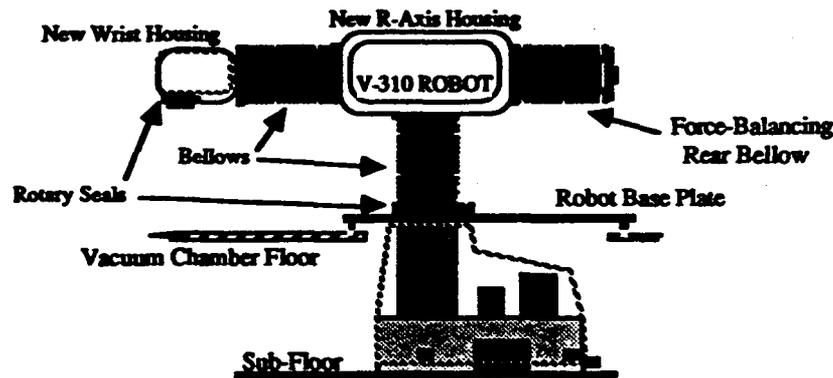
Figure 6. Modified E-310 Robot

Component modifications

The main housings, for the wrist and the R-axis, are replaced with new housings which are designed to be vacuum-compatible and interface with the bellows and the rotary seals. A special feedthrough is designed for interfacing through the wrist to the end-effector. Otherwise, all internal components are left unchanged from the original E-310 robot.

6. Future Work

The vacuum compatible version of the GMF E-310 as modified by the CRSM is scheduled for completion in Spring, 1987. Before then, work will be done to develop appropriate vacuum-compatible end-effectors for use in high vacuum environments. A cooperative venture with Yaskawa of Japan will involve basic research into vacuum robotics and applications. Yaskawa has developed *axial gap pulse motors* especially for use in vacuum. They make use of magnetic stainless steel for the motor body, have a special coating on the coil, and have been specifically designed to prevent heat build up. Research is continuing into *non-contact* drive mechanisms which would allow the elimination of lubricants.

7. Conclusions

The modification of an existing robot for a specific task at high vacuum has been described. Vacuum processing will become increasingly important as the need for ultraclean manufacturing grows. Vacuum-compatible robots will be necessary workers in this harsh environment. The CRSM is developing robot and end-effector technologies to be used for vacuum processing.

8. Acknowledgements

9. References

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