HIGH PRECISION MICRO POSITIONING SYSTEMS USED IN UHV APPLICATIONS

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ABSTRACT

The advantages of miniaturisation, e.g. low masses, low power consumption and small dimensions open new fields of applications for powerful micro actuators in areas dealing with particular environmental conditions like ultra high vacuum or wide temperature ranges. In fact these kinds of applications are mostly challenging positioning tasks, such as the sensitive movement or exact adjustment of sensors, optical devices, probes and tools. In addition to their miniaturised dimensions and low weight the micro gears should offer a backlash-free and precise angular transmission behaviour for such applications.

The Micro Harmonic Drive® gear is the world´s smallest zero-backlash gear system. Originally invented in 2001 by Micromotion GmbH this innovative gear design has successfully been transferred from a research environment into numerous industrial applications. The combination of high reduction ratio, excellent repeatability, high efficiency and high torque capacity offered by this gear principle make it highly suitable for precise positioning applications in semiconductor manufacturing equipment, medical devices, measuring equipment, optical devices as well as ultra high vacuum, aircraft and even spacecraft.

This micro gear, with an outer diameter of down to 6 mm and an axial length of only 1 mm in the smallest currently available size, provides gear ratios between 160 : 1 and 1000 : 1 in a single stage [1]. These high ratios are necessary to convert the very high rotational speeds of up to 100,000 rpm and very low output torques in a range of some µNm provided by current micro motors [2], [3] into lower speeds and higher torques as required by real applications in industrial machines and equipment. The gear is manufactured by a special production process, called “Direct-LIG”, by which the individual gear components are formed galvanically in a 3-dimensional mould produced from a photoresist using X-ray lithography.

However actuators for applications in areas like UHV, Cryo technics, aircraft and spacecraft have to deal with further requirements in addition to properties like zero backlash, high positioning accuracy and extreme demands to reduced mass and dimensions. Due to its unique functional principle the Micro Harmonic Drive® gear offers the possibility to operate at extreme environmental conditions. To be able to use actuators reliably also at extreme environmental conditions, like UHV or wide temperature ranges, there have to be fulfilled special arrangements in relation to the built-up, the materials used and in particular to the lubrication system. The Micro Harmonic Drive® gear provides the basics to be used in such applications. Important properties of the Micro Harmonic Drive® gear are:

- The possibility to use a dry lubrication system
- The single components like housing, shafts, bearings up to the single gear wheels are made of high-strength and corrosion-resistant materials
- Due to its functional principle the gear system consists of only a few components and therefore it has a high reliability.

Based upon this unique principle of a micro gear system this paper will explain various micro positioning systems for rotational and linear movements already applied in UHV or space applications. The Micro Harmonic Drive® representing the key element in these positioning systems combined with UHV suitable stepper drive technology enables novel micro positioning systems for such applications with the following advantages:

- An extreme low weight down to few grams
- A simple and therefore reliable controlling technique
- A low energy consumption
- Positioning movements down to single nanometers
- A reliable and robust operating behavior.

1. INTRODUCTION

The Micro Harmonic Drive® gear is now established in the precision machine market as an ideal solution for precise positioning applications [4]. This gear is manufactured using a modified LIGA process, called Direct-LIG. This allows the cost-effective production of

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extremely precise metallic gear components. The manufacturing of the tiny structural dimensions of the gear wheels of the Micro Harmonic Drive® gear is carried out by means of photolithographic processes. In order to be able to keep tolerances in the sub-micrometer range and also to exploit the properties of metallic gear wheels the "Direct LIG" process is used. The Direct LIG process is based upon the LIGA process [5] and includes the two steps Lithography and Electroplating (see Fig. 1).

a) b)

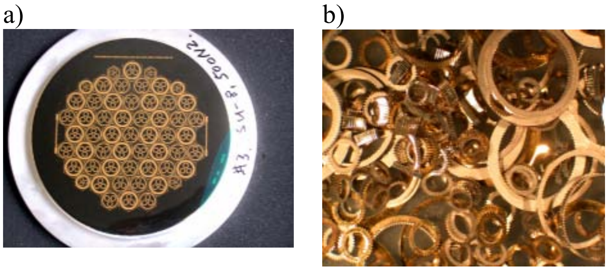

Figure 1: a) X-ray mask and b) electroplated metal micro gear wheels

The structures of the gear wheels are situated as a gold absorber layer on an X-ray suitable mask. The mask pattern is copied through a projection step with high precision into a thick photoresist. To be able to manufacture structures of a height up to 1 mm and simultaneously to keep tolerances less then 1 µm synchrotron radiation is necessary [6]. After the irradiation the unexposed areas can be developed with a particular solvent. The negative mould of the gear wheels inside the photoresist is galvanically deposited using a nickel iron electrolyte. Due to the high yield point of 1.800 N/mm², the low elastic modulus of 135.000 N/mm² and its good fatigue endurance this electroplated alloy possesses the necessary properties for perfect functioning of the flexible gear wheels of this micro gear system (see Fig. 2).

Figure 2: Micro gear wheels fabrication on a silicon wafer

Beside the extremely high accuracy and the possibility to have a resolution in the range of a few nanometres the Direct LIG process offers additional new possibilities to shape the profile of a tooth not available when using classical cutting production methods. Using photolithographic production methods there is no need during the design of the profile of gears to consider the kinematics of tools, the fixture during machining or the behaviour of tool wear. Because the tooth shape is copied through a projection step the freedom of design in the lateral direction is much higher. Additionally there is no conjunction between the lateral complexities of the components to be manufactured and the production costs, i.e. the production costs are independent of the number of teeth or whether an inside or outside toothing is created. However, in the direction of the third dimension it is only possible to vary the width of the teeth. In this direction it is not possible to vary the shape of the tooth profile.

Recently there is increasing demand for micro gears for applications in a vacuum. In the fields of semiconductor manufacturing, pharmaceuticals manufacturing and materials research there is a trend to locate various process steps or analysis tasks in a high or ultra-high vacuum environment. This presents new and difficult problems to overcome for manufacturers of gears or actuators. To enable these products to be used in a vacuum environment special or dry lubricant must be applied and also special mechanical design modifications must be made. Micromotion GmbH, the manufacturer of the Micro Harmonic Drive®, has undertaken a development project involving tribological coatings to allow the use of this gear in such applications.

2. THE MICRO HARMONIC DRIVE®

The Micro Harmonic Drive® gear is currently the world's smallest zero backlash gear system (Fig. 3). The principle of operation is similar to the conventional „macro-technological" Harmonic Drive® gear [7], with the difference that the Wave Generator consists of a planetary gear stage. This enables very large reduction ratios in a small envelope. This is necessary, because most currently available micro-motors only produce adequate torque at very high output speeds, and a high reduction ratio then helps provide sufficient torque at an acceptable speed for practical motion control applications. The planet wheels are hollow and elastically deformable, with the result that backlash can be eliminated by pre-loading the gears in the planetary gear stage.

Figure 3: Micro Harmonic Drive® gearbox and actuator

Fig. 4 shows the basic components of this gear, which uses only 6 components to achieve reduction ratios between 160:1 and 1000:1. These ratios are necessary to create adequate torque from currently available micro-motors, which are capable of rotational speed up to 100000 rpm, but only offer torques of a few µNm.

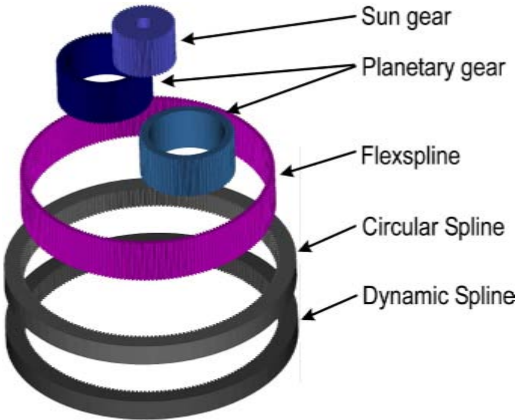

Figure 4: Components of Micro Harmonic Drive® Gear

The principle of operation is the same as "macro-technological" Harmonic Drive® gears as used in large scale industrial robots. The basic elements of the Micro Harmonic Drive® gear system are the Wave Generator consisting of two planetary wheels and a sun gear wheel and the three gear wheels

- Flexspline,
- Circular Spline and
- Dynamic Spline.

With respect to the planned miniaturization of the Micro Harmonic Drive® the planetary gear configuration for the Wave Generator possesses the following advantages:

- All gear components can be manufactured using the high precision Direct-LIG technique
- The assembly effort can be minimized, because the Wave Generator consists of only three components
- The total reduction ratio of the gear increases due to the planetary gear. This design can therefore flexibly adapt the very high
- rotational speed of micro motors in only one stage to the specific requirements of a given application
- This variant of the Wave Generator possesses only a low moment of inertia and therefore enables a highly dynamic positioning performance

By using a planetary gear for the Wave Generator it is possible to vary the total ratio of the Micro Harmonic Drive® over a large range. For the shown gear size, reduction ratios from 160 up to 1000 can be realized in a single stage.

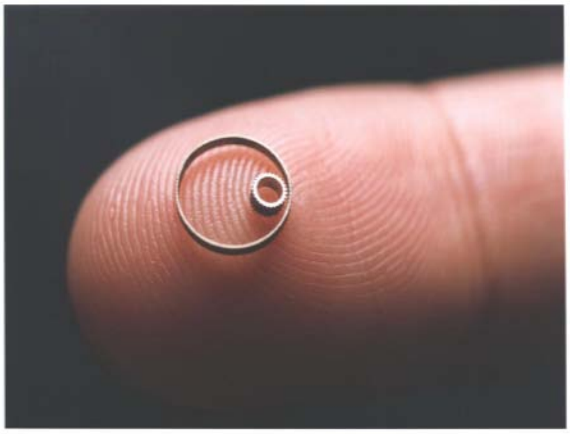

Figure 5: Gear wheels in Nickel-Iron alloy

Excluding the input and output bearing arrangements the outer dimensions of the Micro Harmonic Drive® are 1 mm axial length and 8 mm in diameter. A gear module of 34 µm must be used to realize the necessary high reduction ratio and the small dimensions simultaneously. (see Fig. 5).

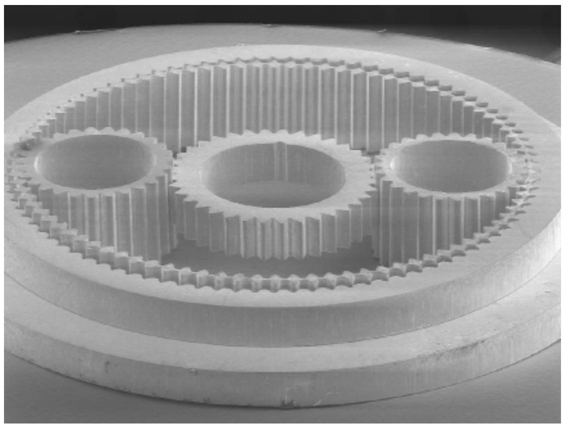

Figure 6: Micro Harmonic Drive® gear component set

Fig. 6 shows a REM picture of the complete component set. It can provide reduction ratios between 160:1 and 1000:1. In order to allow easy integration in a wide range of different applications the component set is mounted inside a Micro gearbox of the MHD series, which is available in two sizes, either with an input shaft or for direct coupling to commonly available micro-motors [8].

The gear component set is typically mounted inside a gearbox (see Fig.7) with an output shaft mounted in pre-loaded ball bearings. The gearbox can either be directly coupled to a micro-motor, or can be provided with an input shaft, so that the motor can be mounted off-axis. A hollow shaft with an inner diameter of up to 1.5 mm passes along the central axis of rotation of the gearbox.

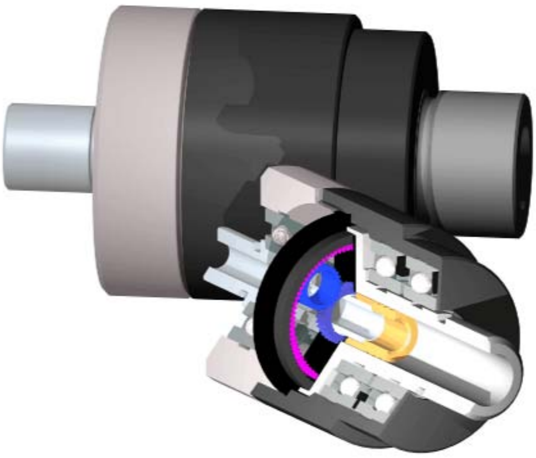

Figure 7: Micro Harmonic Drive® MHD gearbox

This solution provides the machine designer with numerous advantages:

- Miniature dimensions yet zero backlash
- Excellent repeatability for precise positioning
- High dynamic performance for fast indexing applications
- Very long operating life
- Very high reliability
- High efficiency to avoid power losses
- Extremely flat design for compact gearbox dimensions
- Low mass for applications in portable devices or in moving structures
- Applicable under extreme environmental conditions
- Robust, accurate output bearing arrangement
- Hollow shaft capability
- High reduction ratios for low-loss torque conversion and easy control

3. MICRO POSITIONING SYSTEMS BASED ON THE MICRO HARMONIC DRIVE® GEARBOX

In the field of optical systems there is a need for high precision linear actuators. An example therefore is represented by the world smallest Micro Linear Pusher based on the Micro Harmonic Drive® technology. By integrating Micro Harmonic Drive® gears within this micro linear adjustment system, with the advantages such as reliability, positioning accuracy, zero backlash, it has been possible to develop an extremely compact and light-weight linear positioning system. The backlash free micro linear actuator offers a cross section of 10 x 10 mm^2 with a mass of only 22 g and enables a travel range up to 25 mm (see Fig. 8).

Figure 8: Micro Linear Pusher

Such actuators enable to realise a resolution down to 0.002 µm and speeds up to 2,5 $^{mm}/_{s}$ respectively. Due to the preloaded spindle nut system the repeatability is ±1 µm and the maximum forces are 12 N.

Figure 9: Eccentric actuators: tiny and robust micro systems

Eccentric actuators are characterised by a simple system design coupled with high precision. The combination of a micro gear box with zero backlash eccentric mechanism enables the realisation of extremely lightweight, space-saving positioning systems for highly precise adjustments in submicron range (see Fig. 9). On account of their compact external dimensions and extremely low weight of less than 10 grams, systems of this type are also ideal for integration in highly dynamic processes. The repeatability of such systems achieves up to 0.05 µm. These systems offer easy integration also in extreme operating environments such as ultra high vacuum.

There are many micro adjustment tasks requiring movements in three degrees of freedom (see Fig. 10).

Figure 10: 3-axes micro manipulator

The 3-axis-micro-manipulator, with a diameter of only 36.2 mm and a axial length of less than 50 mm, features two linear and one rotational axis. The linear axis are driven using a cam arrangement, which move a small table in X- and Y-direction. The table carries the theta-axis actuator. This design offers following advantages:

- Sub-µm accuracy
- Easy controllability (stepping motors are used for all axes)
- Low mass (<50 g)
- Highly dynamic performance.

Current solutions of positioning systems for applications needing a resolution in the range of some single nanometres involve some significant problems. The idea of the invention of the nanostage is to use a conventional servo motor technique in combination with high precision compliant mechanisms. So the behaviour of the actuator is well known and easy to control. The most positioning systems with a resolution in the range of some nanometres are based on piezo electrical effects. By using such a kind of technique one has to deal with several drawbacks:

- Loss of position if there is an interruption in the power supply
- Local abrasion, particularly for inch-worm type drives
- A direct measurement system is necessary
- Necessity of a cost-intensive controller
- Overshooting during positioning
- Short travel range in correlation to the size

The particular feature of the nanostage is the combination of a high precision and high resolution eccentric mechanism with the kinematic structure of a monolithic flexure hinge. Due to the use of a stepper motor the nanostage needs only a very simple controlling technique and provides simultaneously a very high resolution due to the transmission ratio of 1000:1 of the micro gear box (see Fig. 11).

Figure 11: The Nanostage: conventional power train suitable for extreme requirements on the accuracy

The flexure hinges fulfil the following functions: the guidance system is realised with two parallel flexure hinges suitable for movements in the range of single nanometres and an additional reduction system transforming the big movement of the eccentric mechanism to a resolution in the range of single digit nanometres. The build up of the flexure hinges is done in a monolithic manner to avoid errors of assembly. Such a system offers a step width of less then 3 nm and a repeatability of less than 5 nm

4. MICROGEARS FOR VACUUM APPLICATIONS

Vacuum technology is an increasingly important field, both in technological and commercial terms. In addition to space applications this enabling technology is essential for many new products, production processes and research activities in the fields of semiconductor manufacturing, optics manufacturing and pharma-ceutical production. A clean environment, free from particles and with closely controlled pressure, is essential for an increasingly wide range of modern production processes. Only in such an environment can particular processes be executed, or products with the required quality be produced.

Applications in a vacuum environment are a particular challenge for motion control components. Special attention must be paid to the selection of materials, selection of lubricants and to methods of energy transfer. The precise and reliable movement of objects in a vacuum is only possible with specially developed mechanical and electrical power transmission components.

The advantages of a vacuum environment are being increasingly recognised for a wide range of modern manufacturing and measurement processes. These processes often involve the precise manipulation of a workpiece, tool or probe within a clean environment. Given that humans are a major source of contaminants there is also an additional trend to the complete automation of such processes. Last, but not least, the motion control components necessary for these precise movements are themselves increasingly located in the vacuum environment. This avoids the need for expensive and often imprecise mechanical feed-throughs to convey mechanical movements into the vacuum environment from outside.

The logical consequence is that the demand for vacuum-compatible motion control components is growing quickly. This demand is growing particularly strongly for miniaturised power transmission components, because the workpieces, tools or probes to be positioned are themselves often very small in scale.

Developing motion control components with small dimensions, in the range of a few millimetres, is an additional challenge for the development of vacuum-compatible gears and actuators. The materials used must be chemically resistant, have a low outgassing rate, exhibit a low vapour pressure and also exhibit acceptable thermal expansion characteristics. The lubricants and adhesives used must also withstand the demands of the vacuum environment [9]. These complex requirements are surely the main reason that miniaturised vacuum-compatible gears and electro-mechanical actuators have not been readily available in the past.

The designers of vacuum equipment have therefore been forced into a compromise. In terrestrial applications they have either had to mount the power transmission components outside the vacuum and use mechanical feedthroughs to bring movements into the vacuum, or have been forced to use "unconventional" motion control components. These components, such as piezo-actuators, are either very expensive, difficult to control or have poor positioning performance characteristics.

The demand for miniaturized electro-mechanical motion control components, that are highly precise, easy to control and affordable is therefore very large.

5. MODIFICATIONS FOR VACUUM APPLICATIONS

As mentioned above, a number of modifications must still be made, in order to allow reliable operation in a high vacuum or ultra high vacuum environment [10]. Even though the standard gearbox features high quality materials and a high level of corrosion resistance there are still some parts that must be modified or replaced. The standard output bearings are replaced by dry lubricated bearings with specially coated raceways.

Depending on the level of vacuum the gear itself is either lubricated with special vacuum-compatible grease, or is provided with dry lubrication supported by a special galvanically applied tribilogical coating of the gear teeth (Fig. 12). A further detail design modification concerns the adhesives used to fix the individual gear components. Here, too, a special UHV-compatible adhesive is used. All these modifications have been tested successfully at pressures as low as 10^{-12} mbar.

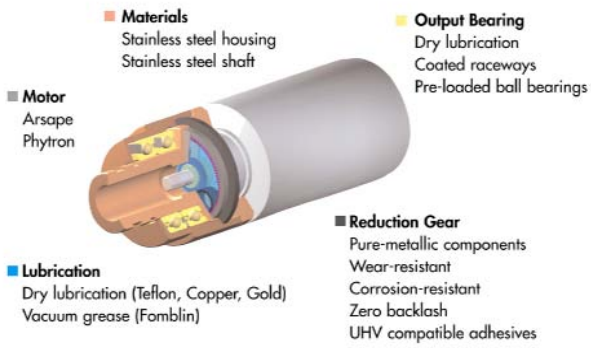

Figure 12: Special modifications for vacuum applications

Due to these modifications and the high strength of the Nickel-Iron alloy, the gear system can be sterilized and can be used over a very wide temperature range (-180° C to +200° C).

6. CONCEPTS OF MICRO POSITIONING SYSTEMS IN UHV

This innovative Micro gear is already being used in practical terrestrial vacuum applications. Fig. 13 demonstrate a rotational positioning system suitable for ultra high vacuum down to 10^{-12} mbar. This actuator consisting of a Phytron stepper coupled with UHV suitable Micro Harmonic Drive® gear box. The bearings of the stepper motor have a dry coating with gold and can fulfill 200 steps per revolution.

Figure 13: Rotational micro positioning system based on a UHV suitable Micro Harmonic Drive® gear box (Source: DESY, Hamburg)

The housing and shafts of the Micro Harmonic Drive® gear box are made in stainless steel. The bearings and gear wheels are dry coated with Dicronite combined with molybdenum disulphate. The actuator has a repeatability of 0.005°.

Fig. 14 demonstrates a linear actuator suitable for ultra high vacuum based on Micro Harmonic Drive® technology. This miniaturised actuator is driven with a Phytron stepper motor and has a repeatability of 1 µm in fullstep mode. The travel range amounts to 25 mm. The bearing and gear component set has a dry lubrication system.

Figure 14: Linear micro positioning system (Source: DESY, Hamburg)

To transform the rotational movement into a linear movement a linear ball spline made and a linear ball spline made of stainless steel and dry coating with Dicronite is used.

A typical example is a new micro-polarimeter developed at BESSY in Berlin (Fig. 15). This high precision, high vacuum compatible (UHV) polarimeter is a multipurpose instrument which can be used as a self-calibrating polarization detector for linearly and circularly polarized UV- and soft X-ray light. It can also be used for the characterisation of either reflection or transmission properties (reflectometer) or polarising and phase retarding properties (ellipsometer) of any optical element. This device is also used to identify the concentration of elements featured in thin magnetic coatings using, for example, the magneto-optical Kerr effect in the soft X-ray region. Fig. 9 shows the complete sub-assembly comprising two vacuum-compatible Micro gearboxes, driven by a single vacuum-compatible motor.

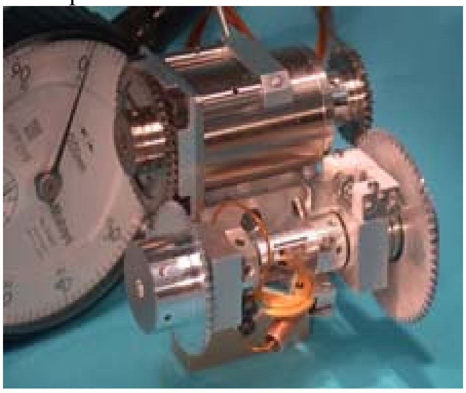

Figure 15: UHV Micro-Polarimeter (Source: BESSY, Berlin)

One Micro gearbox is used to accurately position the deflection mirror, while the other is used to position the detector. The deflection angles of the mirror and detector have a fixed relationship, and this is achieved by using two spur gear stages with different ratios as input stages for the two Micro gearboxes. The spur gears are mounted on the input side of the backlash-free gears The high reduction ratio of the Micro Harmonic Drive® gear has the result that the backlash in the spur gear stage has no noticeable effect on the positioning accuracy of the mirror or detector. A repeatability of ±20 seconds of arc is achieved for both rotational axes. Importantly, this is achieved with open loop positioning control. The motor used is a vacuum-compatible stepping motor from Phytron and no additional position measurement system is required.

The Micro Harmonic Drive® gear is foreseen for applications in space mechanisms. The miniature dimensions, low weight and excellent positioning accuracy enable completely new design solutions for positioning actuators and mechanisms. A typical example is the use of the Micro Harmonic Drive® gear in an electro-mechanical sub-assembly for focussing the objective of different cameras, developed by the Institute of Planetary Research, Berlin. This institute is part of the German Aerospace Research Centre (DLR) and has developed the camera for use on a planetary rover vehicle.

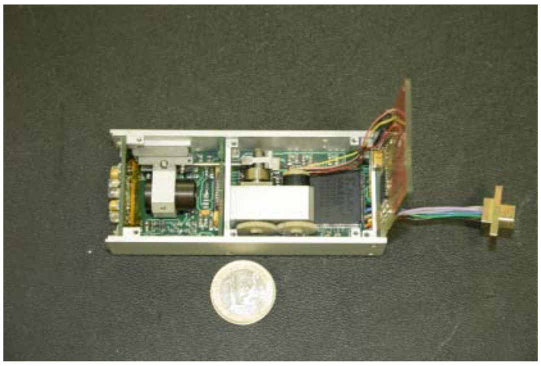

Figure 16: Focusing Mechanism for camera
(Source: DLR Institut für Planetenforschung, Berlin)

The mechanism is used to move a lens in front of a CCD chip in a camera (see Fig. 16, Fig. 17). The actuator must withstand temperatures as low as –180°C and pressures as low as 10^{-9} bar. The absence of backlash, small dimensions, as well as the proven UHV-compatibility of the Micro Harmonic Drive® gear was the key arguments leading to this design. Micromotion GmbH is supplying a complete sub-assembly, comprising a hollow-shaft gear (to allow easy evacuation), motor and pre-loaded eccentric arrangement to provide the linear stroke.

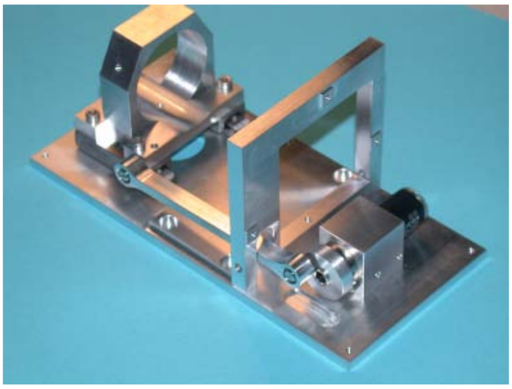

Figure 17: Focussing Mechanism for a further camera
(Source: DLR Institut für Planetenforschung, Berlin)

The camera lens is mounted on a carriage, moved axially by the eccentric mechanism, mounted on the output of the Micro Harmonic Drive® gearbox. This configuration avoids the need for mechanical limits, because if the motor moves too far then the eccentric mechanism causes the lens to move back in the direction from which it came. The gearbox is driven, in turn, by a stepping motor. This solution is dramatically lighter and more compact than previous designs.

A further field of applications is represented by the manipulation and assembly of components inside a vacuum environment. A typical example therefore is the usage of a Micro Harmonic Drive® gear combined with a stepper motor of the company Arsape in a SEM environment. In this application the actuator is necessary to move and adjust a micro gripper inside a SEM and to manipulate micro components afterwards during observing them by SEM (see Fig. 18).

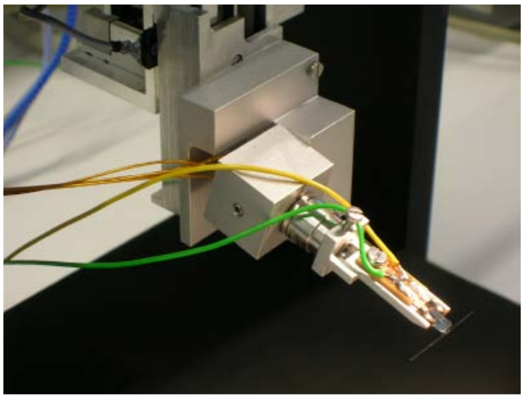

Figure 18: alignment of a micro gripper
(Source: CAESAR, Bonn)

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