# MINIATURE ZERO-BACKLASH GEARS AND ACTUATORS FOR PRECISION POSITIONING APPLICATIONS

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## ABSTRACT

The Micro Harmonic Drive gear, first invented in 2001 by Micromotion GmbH in co-operation with the Institute for Microtechnology in Mainz, Germany, is already successfully established in a wide variety of precise positioning applications in industrial machines.

Based on experience gathered in terrestrial vacuum applications there are now first applications in space mechanisms. The miniature dimensions and low weight enable completely new design solutions for positioning actuators and mechanisms. The paper describes the developments made to qualify the Micro gear for space applications, including extensive tests with various different lubricants.

The paper also describes in detail a practical application of the Micro gear in a camera under development by the DLR Insitute for Interplanetary Research in Berlin, Germany.

## 1. INTRODUCTION

The Micro Harmonic Drive® gear is now established in the precision machine market as an ideal solution for precise positioning applications. This gear is manufactured using a modified LIGA process, called Direct-LIG. This allows the cost-effective production of extremely precise metallic gear components. With a diameter of 10 mm or less and with a tooth module of 34 µm or less the Micro Harmonic Drive® is the world's smallest zero backlash gear system. It's excellent repeatability of less than 10 seconds of arc is the basis for a variety of applications for machines in the semi-conductor industry, optical devices and medical equipment.

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. Special or dry lubricants must be applied and also special mechanical design modifications must be made to enable these products to be used in a vacuum environment. 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. In this paper the various steps necessary to allow the use of the gear in a vacuum are presented, as well as an application in a micro-polarimeter for use in synchrotron research. The experience gained in such terrestrial applications is forming the basis for new projects for the space environment. A current project at the Institute of Planetary Research of the German Aerospace Research Centre (DLR) involves the use of a Micro Harmonic Drive® in the focusing mechanism of a camera, under development for a future Mars mission.

## 2. THE MICRO HARMONIC DRIVE®

Micro gears are not a particularly recent development and micro-spur gears or micro-planetary gears have been available in the market for a number of years. However, these products suffer from poor positioning accuracy and are therefore rarely used for positioning applications in machines or instruments. These previous solutions either have backlash, or only permit very light loads. What is needed are Micro gears that are not only very small in size, but also feature high repeatability, zero backlash, high reduction ratios and a low parts count. These requirements inspired the development of a new Micro gear, the Micro Harmonic Drive® gear [1] (Fig. 1). This gear was developed by Micromotion GmbH in Mainz, in co-operation with the Institute for Microtechnology, also located in Mainz in Rhineland-Palatinate, Germany. The Micro Harmonic Drive® gear is currently the world's smallest zero backlash gear and in combination with a specially developed motor from Maxon Motors, Switzerland, forms part of the world's smallest zero backlash positioning actuator (Fig. 2).

Fig. 1 Micro Harmonic Drive® gearbox and actuator

The principle of operation is similar to the conventional „macro-technological“ Harmonic Drive® gear [2], 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.

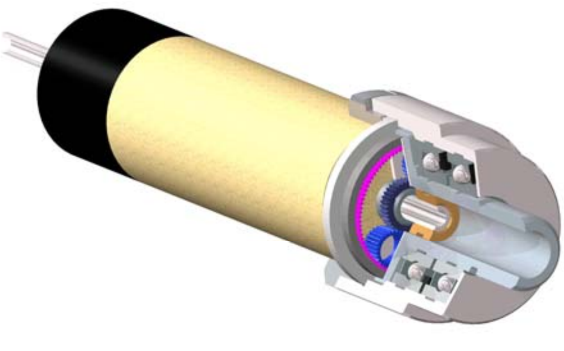

Fig. 2 World’s smallest zero backlash actuator (diameter 8mm, length 31,3 mm)

Fig. 3 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 100 000 rpm, but only offer torques of a few µNm. Fig. 3 shows the gear mounted to a pancake-type micro-motor.

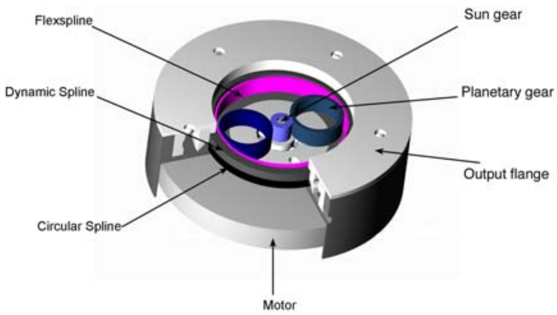


Fig. 3 Micro Harmonic Drive® gear components

As can be seen from Fig. 4 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.

The Wave Generator deflects the elastically deformable Flexspline elliptically across the major axis. Due to that the teeth of the Flexspline engage simultaneously with the two ring gears - Circular Spline and Dynamic Spline - in two zones at either end of the major elliptical axis. Across the minor axis of the elliptically deflected Flexspline there is no tooth engagement. When the sun wheel of the Wave Generator rotates, the zones of tooth engagement of the Flexspline travel with the angular position of the planet wheels of the Wave Generator. A small difference in the number of teeth between the Flexspline and the Circular Spline (the latter has two teeth more) results in a relative movement between these gear wheels. After a complete rotation of the planet wheels of the Wave Generator the Flexspline moves relative to the Circular Spline by an angle equivalent to two teeth. The Dynamic Spline is used in the flat type gear system as the output element and has the same number of teeth as the Flexspline and therefore the same rotational speed and direction of rotation. 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

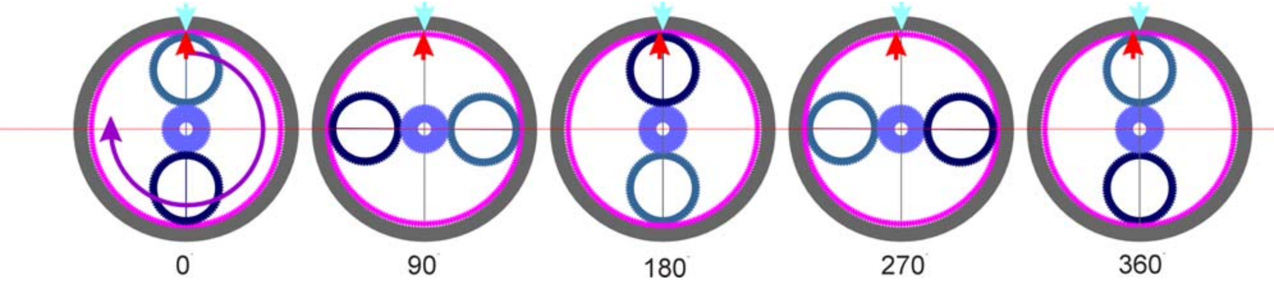


Fig. 4  Principle of Operation

- 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.

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.

The single gear wheels of the Micro Harmonic Drive® are manufactured by electroplating and consist of a nickel-iron-alloy. Due to the high yield point of 1.500 N/mm², the low elastic modulus of 165.000 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. 5).

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 from Arsape, Escap, Faulhaber, Maxon, Mymotors, Myonics, Phytron etc. [3].

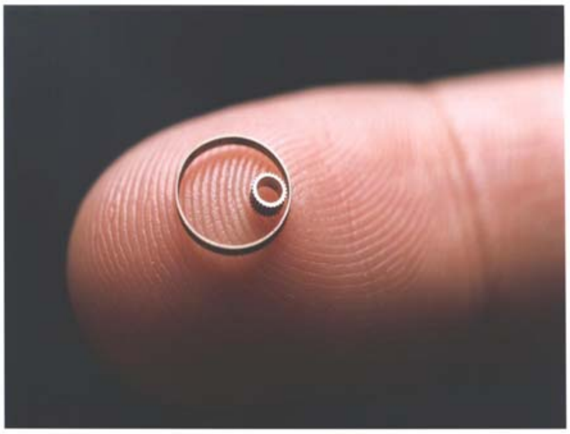

Fig. 5  Gear wheels in Nickel-Iron alloy

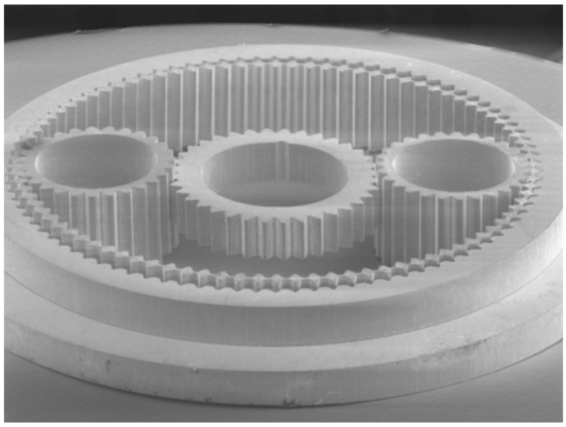

Fig. 6  Micro Harmonic Drive® gear component set

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 mm passes along the central axis of rotation of the gearbox.

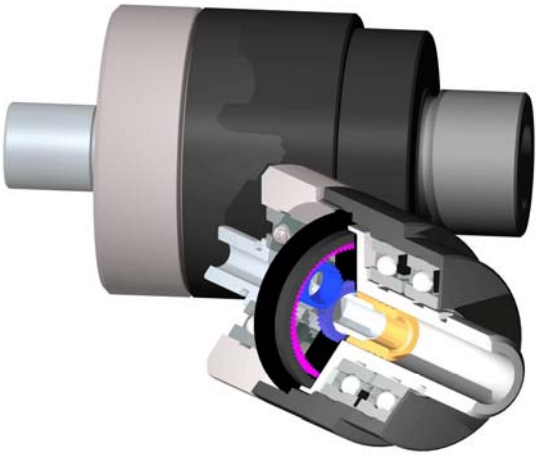

Fig. 7 Micro Harmonic Drive® MHD gearbox

This solution provides the machine designer with numerous advantages:

**a) Miniature dimensions yet zero backlash**

The Harmonic Drive gear stage is backlash-free by nature and the elastically deformable planet wheels eliminate backlash in the planetary stage.

**b) Excellent repeatability for precise positioning**

The zero backlash of the Micro Harmonic Drive® gear provides a repeatability in the range of a few seconds of arc. This enables positioning tasks to be carried out with sub-µm accuracy

**c) High dynamic performance for fast indexing applications**

The high torque capacity and low moment of inertia enable extremely fast accelerations of up to 550 000 rad/$s^2$ at the input shaft. This corresponds to an acceleration of the motor shaft from 0 to 100 000 rpm in 25 milliseconds. This, in turn, enables extremely fast angular movements e.g. a rotation of 180 ° in less than 80 milliseconds.

**d) Very long operating life**

The MHD Micro gearboxes have an operating life of 2500 hours at rated operating conditions, that is, at rated input speed and rated output torque. This corresponds to many million operating cycles in practical applications and the operating life of the Micro gearbox is typically equivalent or longer than the expected operating life of the machine in which it is used. The “life-cycle-costs” are therefore considerably lower than for other solutions with a lower initial cost.

**e) Very high reliability**

The MHD gearbox has a significantly higher MTBF (**M**ean **T**ime **B**etween **F**ailure) rating than other Micro gears. This is mainly the result of the far lower number of parts, compared to other gears. A planetary Micro gear with a reduction ratio of 1000:1 typically has 25 individual gear wheels, whilst the comparable Micro Harmonic Drive® gear has just 6.

**f) High efficiency to avoid power losses**

The Micro Harmonic Drive® gear has an efficiency of up to 82% at rated operating conditions. This is also significantly higher than for other Micro gears. The reason lies in the small number of tooth engagement areas. A planetary gear with ratio 1000:1 has 30 regions of tooth engagement, whilst the comparable Micro Harmonic Drive® has just 8.

**g) Extremely flat design for compact gearbox dimensions**

The axial length of the MHD Micro gearbox is independent of the reduction ratio and is less than half the length of other Micro gearboxes for the same output torque and reduction ratio.

**h) Low mass for applications in portable devices or in moving structures**

As can be seen from Table 1, the gearboxes weigh just a few grams. In practical applications this means that the moving masses in the machine can be minimised. This, in turn, can contribute to greater thermal stability and lower temperature rise, both of which are essential in high precision machines. Furthermore, this enables higher accelerations and/or smaller feed drives.

**i) High reduction ratios for low-loss torque conversion and easy control**

The high reduction ratios greatly reduce the load moment of inertia reflected at the motor shaft. The result is that in most practical applications the motor is hardly influenced by the load inertia. In combination with the low input-side moment of inertia of the gear this has the effect that the control of the motor is almost independent of the load inertia over a very large range of load inertias. This makes the control of the motor and setting-up of the control system very easy.

**j) Hollow shaft capability**

The optional hollow shaft can be used to pass laser beams, air / vacuum supply or optical fibres through the centre of the gear or actuator along the central axis of rotation. This can greatly simplify the design of machines where otherwise the laser beam or fibre would need to be diverted around the actuator.

**k) Robust, accurate output bearing arrangement**

The high load capacity of the output bearings (pre-loaded ball bearings in an O-configuration – see Fig. 7) mean that no additional support bearings are needed for the load in most applications. Furthermore, the accurate geometric tolerances (axial and radial run-out less than 5 µm) allow the attachment of load components e.g. mirrors, filters or lenses, directly to the output shaft.

**l) Applicable under extreme environmental conditions**

The use of high quality materials, such as stainless or high-alloy steels for the gearbox housing, input / output shafts and bearings, provides a high level of corrosion resistance, even for standard MHD Micro gearboxes. The Micro Harmonic Drive® gear, which is

| Gearbox size | | **MHD 8** | | **MHD 10** | | |
|---|---|---|---|---|---|---|
| Reduction ratio | | 160 | 500 | 160 | 500 | 1000 |
| Peak torque | [mNm] | 14 | 20 | 24 | 36 | 48 |
| Rated torque | [mNm] | 7 | 10 | 12 | 18 | 24 |
| Repeatability | [arcsec] | 10 | 10 | 10 | 10 | 10 |
| Outer diameter | [mm] | 8 | 8 | 10 | 10 | 10 |
| Weight (with input shaft) | [g] | 3.5 | 3.5 | 5.7 | 5.7 | 5.7 |

Table 1 Key performance data for MHD gearboxes

manufactured in a high strength Nickel-Iron alloy, can be sterilized and can be used over a very wide temperature range (-70° C to +150° C). As will be described subsequently it can also be applied in a vacuum, using grease, oil or dry lubrication, depending on the specific requirements of the application.

## 3. 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 pharmaceutical 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 recognized 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 [4]. 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 miniaturised electro-mechanical motion control components, that are highly precise, easy to control and affordable is therefore very large.

## 4. 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 [5]. 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 a special vacuum-compatible grease, or is provided with dry lubrication supported by a special galvanically applied tribilogical coating of the gear teeth (Fig. 8). 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 $10^{-12}$ bar.

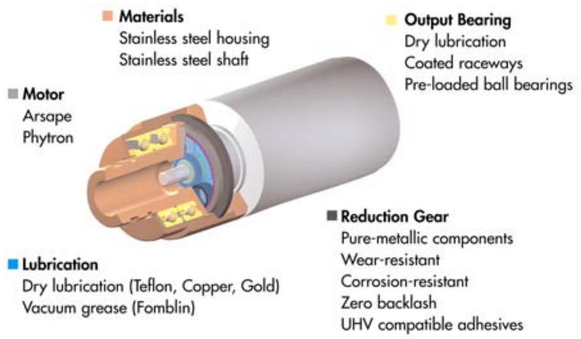


Fig. 8 Special modifications for vacuum applications

## 5. APPLICATION EXAMPLES

This innovative Micro gear is already being used in practical terrestrial vacuum applications. A typical example is a new micro-polarimeter developed at BESSY in Berlin (Fig. 9). This high precision, high vacuum compatible (UHV) polarimeter is a multipurpose instrument which can be used as a self-calibrating polarisation detector for linearly and circularly polarised 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. 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.

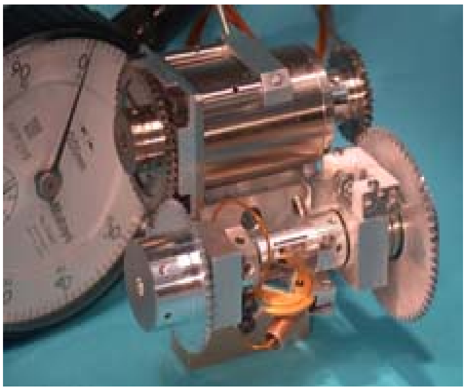

Fig. 9 UHV Micro-Polarimeter (Source: BESSY, Berlin)

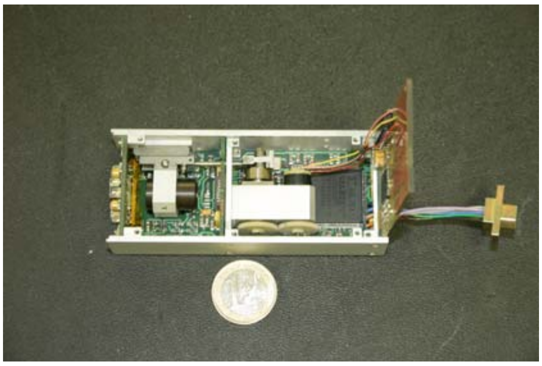

Fig. 10 Focussing Mechanism for camera (Source: DLR Institut für Planetenforschung, Berlin)

Based on the experience gathered in terrestrial vacuum applications the Micro Harmonic Drive® gear is now 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 a camera, 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. The new focussing mechanism will allow the camera to guide the vehicle to surface objects and then undertake microscopic analysis of these objects.

The mechanism is used to move a lens in front of a CCD chip in a camera (see Fig. 10). The actuator must withstand temperatures as low as $–70^{o}C$ and pressures as low as $10^{-9}$ bar. The absence of backlash, small dimensions, as well as the proven UHV-compatability of the Micro Harmonic Drive® gear were 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 of +/- 2.25 mm

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 functional prototype has already been successfully tested and a space-qualified version will be delivered in late 2005.

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