THE MICRO HARMONIC DRIVE®:

A HIGH PRECISION MICRO GEAR SYSTEM MINIATURIZED BY LIGA

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ABSTRACT

Micro gear systems have to adapt the high rotational speed of up to 100.000 rpm and the low output torque in a range of some µNm provided by current micro motors to the requirements of many different applications. In addition to their miniaturized size and low weight micro gear systems must also feature zero backlash and precise angular transmission characteristics if they are to be used in micro positioning applications, e.g. in medical equipment, micro robotics, fiber communications equipment and aerospace applications.

At Micromotion GmbH, the principle of operation of a Harmonic Drive® gear system has been applied to a micro gear system of only 1ámm axial length and 8ámm diameter using the LIGA technique. In addition to its small size the Micro Harmonic Drive® achieves a very high reduction ratio between 500 to 1032á:á1 in a single stage and transmits an output torque of 15ámNm with a minimal torque loss of less than 16áµNm. The individual gear components of the Micro Harmonic Drive® are manufactured from NiFe alloy. With a repeatability and lost motion of less than 10´´ the Micro Harmonic Drive® is ideally suited for applications in high precision micro positioning drive systems.

1. INTRODUCTION

Micro gear systems represent a key element in micro drive systems. Only by using suitable micro gear systems is it possible to apply existing micro motors operating with speeds of up to 100.000 min ^{1} at output torques in the range of some µNm [1] in a wide field of different applications. To access new innovative fields of application in the range of micro drive systems Micromotion GmbH has developed a new generation of high precision and zero backlash micro gear system: the Micro Harmonic Drive® (see **Figure 1**).

Figure 1: *High precision micro gear system based on the Harmonic Drive® principle*

2. THE MICRO HARMONIC DRIVE®

2.1. PRINCIPLE OF OPERATION

The principle of a Harmonic Drive® gear system stands out compared with other gear principles e.g. spur gears and planetary gear systems, because of its high precision and zero backlash transmission properties. Its exceptional properties have been proven for many years in the fields of industrial robots, machine tools, measuring machines, aerospace and medical equipment [2]. Harmonic Drive® gear systems can be classified into the flat type and the cup type (see **Figure 2**). The flat type gear system offers the following advantages, which are particularly important with reference to micro gear systems:

- Small number of components
- A compact design
- The high reduction ratio necessary for micro motors can be reached in a single gear stage.

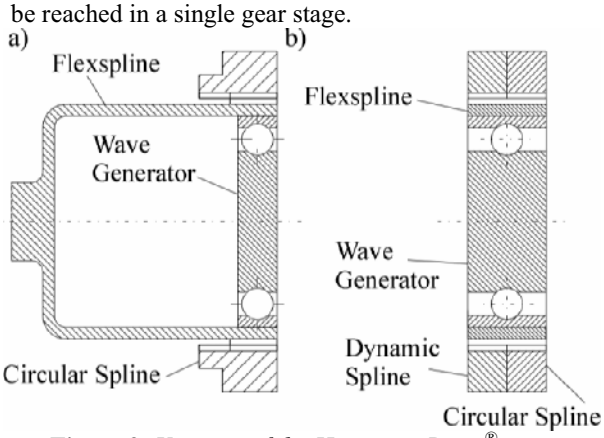

***Figure 2**: Versions of the Harmonic Drive® gear: a) Cup type, b) Flat type*

The basic elements of the flat type Harmonic Drive® gear system are the elliptical Wave Generator and the three gear wheels

- Flexspline,
- Circular Spline and
- Dynamic Spline.

The Wave Gererator 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 (see **Figure 3**). Across the minor axis of the elliptically deflected Flexspline there is no tooth engagement.

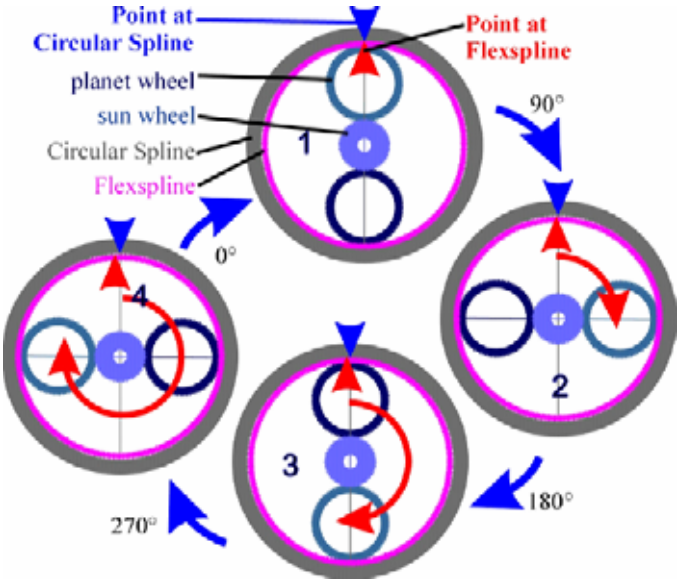

***Figure 3**: Operating principle of the Micro Harmonic Drive® gear*

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.

There are three basic configurations for the Wave Generator: an elliptical ball bearing, a planetary gear arrangement and a two roller link (see **Figure 4**).

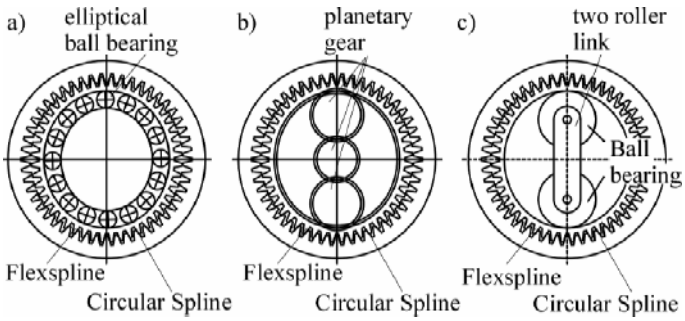

***Figure 4**: Wave Generator: a) elliptical ball bearing, b) planetary gear, c) two roller link*

With respect to the 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 LIGA-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. Only by using different numbers of teeth for the planet wheels and the sun wheel, a family of different reduction ratios can be realized within the same gear envelope. For the shown gear size reduction ratios of 500 and 1032 can be realized in a single stage due to different combinations of planet wheel and sun wheel. 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 (see **Figure 5**).

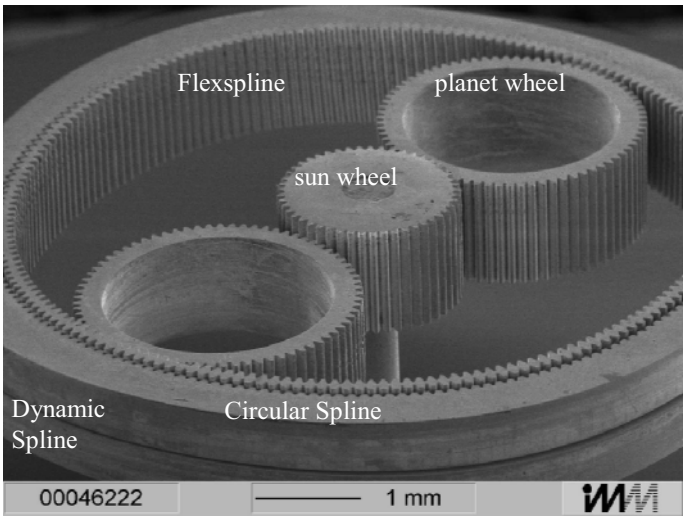

Figure 5: *Components of the Micro Harmonic Drive® Gear*

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 165.000á^{N}/mm² and its good fatigue endurance [3] this electroplated alloy possesses the necessary properties for perfect functioning of the flexible gear wheels of this micro gear system.

2.2 Flexible gear wheels

The Flexspline represents the most challenging component of the Micro Harmonic Drive® (see **Figure 6**).

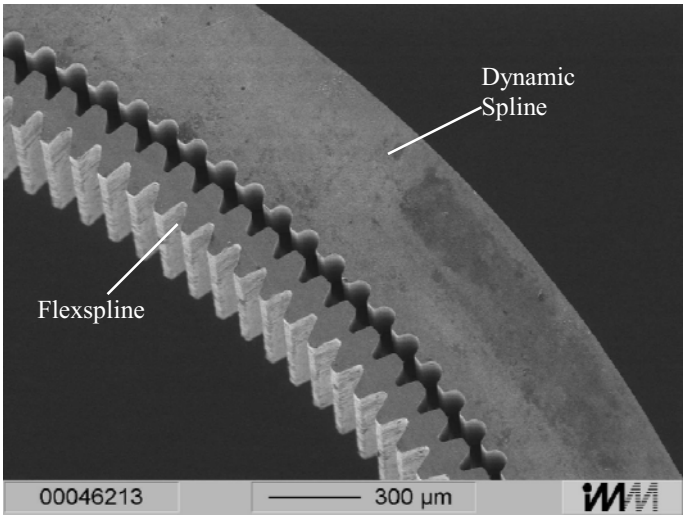

Figure 6: *Internal and external teeth of the Flexspline*

Contrary to conventional gear systems based on the Harmonic Drive® operating principle, the Flexspline of the Micro Harmonic Drive® needs in addition to its very thin ring thickness an internal and external toothing simultaneously. This duplex toothing is necessary due to the planetary gear configuration of the Wave Generator. To achieve trouble-free operation the Flexspline must exhibit uniform deflection behaviour. This is realized by using the same number of teeth for the external and internal toothing. The production of the duplex toothing and the thin ring thickness necessary for low bending stresses when the Flexspline is deflected is made possible by using the LIGA-technique [4]. Because of this technique it is possible to realize a ring thickness in the tooth root of only 40 µm for a tooth width of 1000 µm.

Another component contributing essentially to the zero backlash and precise operating behaviour of the Micro Harmonic Drive® is the flexible planet wheel of the Wave Generator. Both planet wheels have the primary task of realizing the exact deflection of the Flexspline. Additionally the planet wheels have to compensate errors of fabrication and wear of the gear system whilst still providing an exact deflection of the Flexspline. This error compensating property of the planet wheels is made possible by their design as a spring element. Therefore the flexible properties of a tube with a thin ring thickness acting in a radial direction can be used. The planet wheel is designed as a thin ring providing simultaneously enough flexibility to compensate errors yet rigid torsional stiffness. The Flexspline is pressed by the planet wheels simultaneously into engagement with the Circular Spline and the Dynamic Spline. Consequently errors in both zones of tooth engagement are compensated by their spring travel (see **Figure 7**).

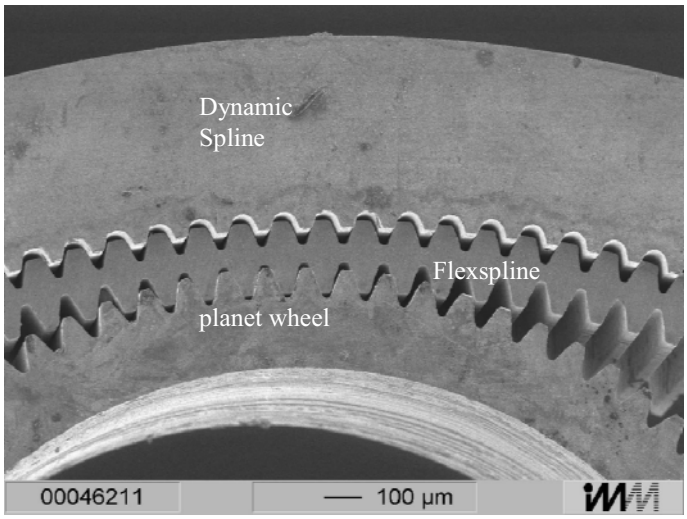

Figure 7: *Zero backlash by means of flexible planet wheels*

As a result both external and internal teeth of the Flexspline are brought into contact with the leading and return faces of the teeth of the meshing gear wheels. The preload of the gear system provided by the flexible planet wheels is the basis for the zero backlash transmission behaviour and high positioning precision of the Micro Harmonic Drive®.

2.3 Simulation of the microgear system

The design of the geometry of the tooth flanks of the gear wheels Flexspline, Circular Spline and Dynamic Spline represents a key stage in the dimensioning of the new microgear. In contrast to conventional gear systems the relative meshing of the Flexspline and Circular Spline teeth involves not a rolling but a primarily radial movement. To be able to execute an exact dimensioning of the teeth, in particular of the geometry of the flanks, it is necessary to compute the exact curves of movement of the Flexspline teeth in relation to the Circular- and Dynamic Spline (see **Figure 8**).

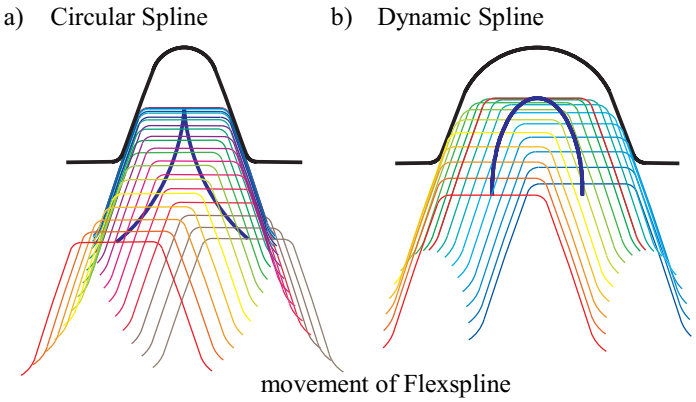

Figure 8: *Relative meshing of Flexspline with a) Circular Spline and b) Dynamic Spline*

These curves of movement serve as basis for an exact dimensioning of the teeth of all the gear wheels of the Micro Harmonic Drive®. Thereby a trouble-free function of the gear system and the precision of movements needed for positioning drive systems can be realized.

The optimization of the geometrical dimensions of the flexible gear wheels of the Micro Harmonic Drive® was executed by FEM analysis.

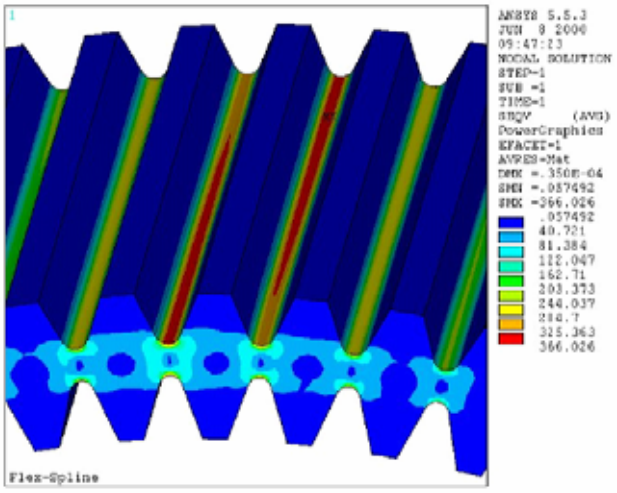

Figure 9: *Stress under load*

The mechanical stress in the Flexspline resulting from the deflection through the wave generator and an external torque load can be exactly determined in dependence of the geometrical dimensioning (see **Figure 9**).

Based on this optimization the gear copes with an output torque up to 35 mNm without going beyond the allowed mechanical reversed bending stress for endurance.

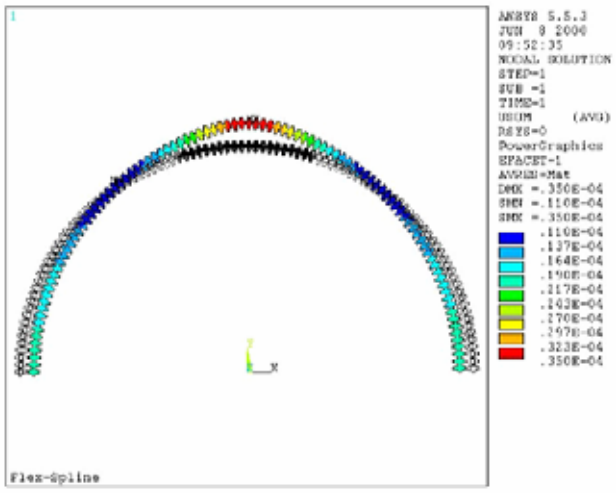

Figure 10: *Deflection of the Flexspline*

Additionally the FEM-simulation allows the exact calculation of the deflection of the loaded Flexspline (see **Figure 10**).

2.4 Experimental analysis and data

The very low friction torque of this zero backlash micro gear system is based on the exact dimensioning of the gear wheels and the high precision reached by using the LIGA-technique for manufacture. In spite of the pre-load of the wave generator, which is necessary to realize a zero backlash gear system, the maximum measured friction torque is only 16 µNm (see **Figure 11**).

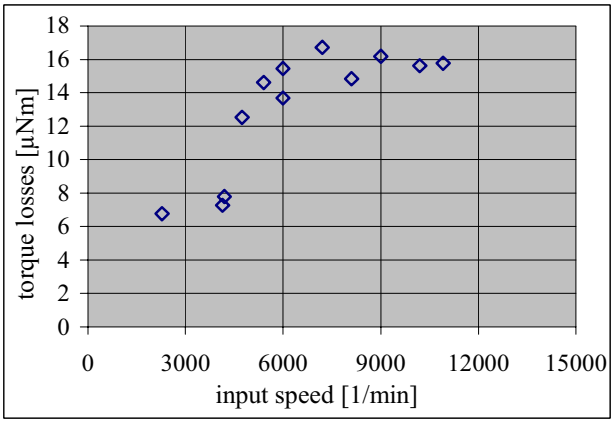

Figure 11: *Correlation between input speed and friction torque*

The measured maximum value of the efficiency of the Micro Harmonic Drive® gear amounts to 40 % for a transmission ratio of 500 (see **Figure 12**).

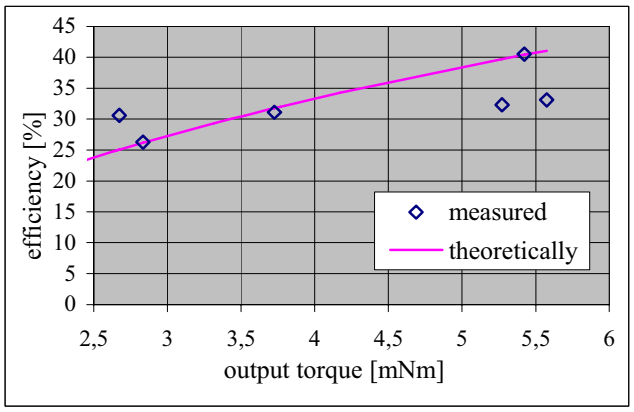

***Figure 12**: Correlation between output torque and efficiency*

The measuring results illustrated in **Figure 12** show the steady increase of the efficiency with increasing output torque. Due to the monotonic increasing trend of the measured points and the progress of the theoretical curve a further increase of efficiency may be expected towards still higher torques

Additionally to its low friction torque and high efficiency the Micro Harmonic Drive® is distinguished especially by its excellent transmission qualities in comparison to other gear systems. The repeatability, lost motion and the hysteresis are suitable criteria to describe the quality of the transmission of a zero backlash gear system operating in positioning drive systems. The hysteresis describes the effects of a changing output load of the angular position of the output shaft of the gear and simultaneously its torsional stiffness. The value of the lost motion describes the angular error, which results by positioning movement from opposite directions.

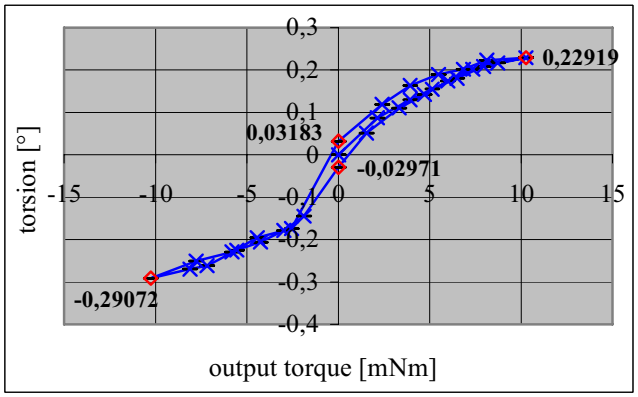

***Figure 13**: Hysteresis of the Micro Harmonic Drive®*

The high efficiency and precise transmission behaviour of the zero backlash Micro Harmonic Drive® is shown clearly by the narrow hysteresis curve and the resultant low hysteresis losses of less than 0,1° (see **Figure 13**).

The most important data and measured values of the realized Micro Harmonic Drive® are listed in **Table 1**.

***Table 1**: Technical gear data*

dimensions:	diameter:	8 mm
	axial length:	1ámm
transmission ratio:		500
		1032
modulus:		34 µm
material:		nickel-iron
efficiency:		40 %
output torque:		10 mNm
torque loss:		16 µNm
repeatability:		±10´´
lost motion:		10´´
hysteresis losses:		0,1°
torsional stiffness:		2,6 $^{Nm}/_{rad}$

Due to its properties, especially its high repeatability and its lost motion lower than 10 arc seconds the Micro Harmonic Drive® is ideally suited for applications in high precision micro positioning drive systems. The Micromotion GmbH, located in Mainz in Rhineland Palatinate, is focused on the development and manufacture of micro gears and micro actuators using the Micro Harmonic Drive® principle.

3. Micro drive systems

The Micro Harmonic Drive can be combined with all currently available micro motors, e.g. stepping motors, AC or DC motors and pancake motors. The combination of the Micro Harmonic Drive® with a pancake motor, represents a powerful and geometrically matching micro drive system (see **Figure 14**).

***Figure 14**: Ultra flat micro drive system*

The pancake motor illustrated in **Figure 14** is distinguished by its small diameter of 12.8 mm and especially by its extremely flat height of 1.4 mm. By combining the ultra flat Micro

Harmonic Drive® and the pancake shaped penny motor it is possible to realize a micro actuator with only 4.3 mm axial length and 13.4 mm diameter. This micro actuator provides an output torque of up to 10ámNm and rotational speeds up to 100 $min^{û1}$ with an operating weight of only 4.3 g. Additionally alternative output bearing arrangements for the Micro Harmonic Drive® can be realized to enable easy integration in a wide range of applications, e.g. an output shaft with preloaded bearings, output shaft with flange bearing and output flange with flange bearing.

4. Applications for micro drive systems

Additionally to their small dimensions micro actuators incorporating the Micro Harmonic Drive® gear offer new advantages due to their low mass, low inertia and low power consumption despite their excellent positioning accuracy and highly dynamic performance.. The precision micro gears and micro actuators from Micromotion GmbH are a key enabling technology for a new generation of miniaturised devices in a wide range of application areas. The Micro Harmonic Drive® is ideally suited to precise positioning applications in the following fields:

- optics, e.g. to adjust lenses and mirrors,
- medical equipment, e.g. to dose drugs or to drive surgical instruments,
- optical communication, e.g. to switch or adjust fibres,
- semicon, e.g. to assemble, handle and adjust semi-conductor components,
- robotics, e.g. to drive axes of micro robots with high accuracy,
- laser technology, e.g. to adjust the beam by means of mirrors or lenses,
- biotechnology, e.g. to dose expensive materials and to adjust pipette probes,
- measuring machines, e.g. to adjust non-contacting sensors
- aircraft and spacecraft, e.g. to control nozzles or valves in nanosatellites.

5. Concluding remarks

New positioning applications in medical equipment, optics, micro robotics and semicon need new drives and gears with extremely small dimensions. Additonally to the size these new applications need a high positioning accuracy and a precise controling. These terms can not be realized by using existing solutions of micro gear systems. The prefered functional principle of the existing solutions is represented by the planetary gear system. This kind of principle needs several stages and therefore a lot of parts. The main disadvantage of the available products is their backlash of several degrees. Therefore a high positioning accuracy is not possible with existing solutions.

The Micro Harmonic Drive® sets new standards. This gear system combines the advantages of a compact construction, a high power density and excellent positioning properties. This all is realized using only six components. The consequences are that the Micro Harmonic Drive® is more precise, smaller, simpler and therefore more reliable than existing solutions.

Micromotion GmbH located in Mainz develops and produces the worldÆs smallest zero backlash micro gear system, the Micro Harmonic Drive®.

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