ULTRA COMPACT AND LIGHT WEIGHT MICRO ACTUATORS SUITABLE FOR SPACE APPLICATIONS

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1 MOTIVATION

In collaboration with DLR, Micromotion GmbH has developed an ultra compact and light weight micro actuator based on the Harmonic Drive principle in order to manage the focussing of an optical lens of a space rover system's camera module. Moreover a modular concept for the actuator's setup has been prepared to hit the demands of further space applications such as of units for adjusting or replacing systemic functional elements to achieve redundancy and by this to increase reliability of subsystems.

The different milestones of this development shall be described in the following by reconsidering the design and working principle, actuator specific requirements related to the environmental conditions in space, fundamental investigation to define functional parameters and associated modifications of the actuator as well as results of first prototypes shall be described.

2 BACKGROUND

Due to extreme small outer dimensions and very low masses of only some single grams the usage of micro actuators in space technology opens a wide range of application based on the potential of exploiting new functionalities and basically new concepts. Low masses as well as small outer dimensions enable to build up satellites in a smaller, lighter and therefore cheaper manner. In addition a reduction of outer dimensions and masses corresponds with a decrease of related effects caused by shocks and vibrations during the launch phase. However more important is the possibility to improve the reliability of the total system significantly by using micro actuators. This could be realized by carrying out an automatic rearrangement of essential components driven by micro actuators if needed e.g. after launch phase or before measurement phase. Reliability also can be improved by an automatic exchange of essential components suffering on wear. A further possibility to increase the reliability is the usage of many micro back-up systems, working independently one from each other and being able to substitute defect systems if needed.

However the operation of drive systems in space applications is challenging especially for micro actuators in respect of vacuum condition, temperature range and radiation exposure. In particular for the scope of micro actuators the limited repertory of space suitable materials causes specific problems: Materials must not outgas, should be non-corrosive, have to be resistant towards radiation and stable for temperature changes with extremely high amplitudes and absolute peak values. Beside the high needs on the material properties the demands on the conceptual design is accordant: Gas pockets have to be avoided and a compensation of thermal expansion of different materials has to be enabled. The lubrication and the joining techniques of the micro systems are confronted with specific requirements, too. Especially the lubricant must not outgas, has to maintain its properties over a long period of time and so should permit a smooth positioning performance with low losses.

For the described development most of these space specific demands had to be met by an adequate choice of working principle, design concept and material portfolio.

3 TECHNICAL DEMANDS AND SOLUTION

For a precise linear positioning of an optical lens of a space rover system's camera module following demands had to be fulfilled:

- positioning range of lens (stroke): 2.5 mm
- positioning resolution: < 100 µm
- load to be moved: lens of outer diameter 11 mm, length 17 mm, mass ca. 3 g
- shock resistance
- UHV compatibility: Outgassing behaviour of the drive chain has to be defined by tests
- suitability for usage at deep temperatures: Storage temperature -180°C, operating temperature -60°C
- high reliability (MTBF) respectively high resistance towards failure of subcomponents (e. g. limit switches)
- available space for complete camera module: 50 mm x 19 mm x 80 mm; in order to obtain enough space for electronics and the optical system the

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drive chain has to be minimized during development.

- maintainable availability and costs of components

By considering these demands following concepts have been reflected to achieve the functionality of a focusing mechanism to perform a precise and reliable linear motion of an optical lens:

A) spindle nut drive
B) rack and pinion
C) eccentric mechanism (linkage)
D) steel tape

In order to hit the described and challenging requirements the concept of an eccentric mechanism (linkage) has been chosen. Basic elements of this drive chain concept are a Micro Harmonic Drive gear system with a reduction ratio of i = 160:1 and an outer diameter of 10mm (Micromotion GmbH) in combination with a stepper motor AM1020 with outer diameter of 10mm and a positioning resolution of 20 steps per revolution at full step mode (PRECIstep S.A.). Main criteria for that decision are:

- The impact of a radial thermal expansion on an adjusted position of the lens in the wake of temperature changes can be compensated by the distinctive, axially symmetric mechanical setup of an Harmonic Drive gear rack.
- The extremely high reduction ratio of 160:1 offered by just one gear stage of a Micro Harmonic Drive gear rack helps reducing the needed space of the drive chain by increasing the positioning resolution at the same time.
- The Micro Harmonic Drive configuration assures a high repeatability (down to +/- 10 arcsec) and therefore offers the possibility to operate even without feedback system in open loop mode. As a consequence maintainable efforts for a controlling of the combination out of a stepper motor and Micro Harmonic Drive gear system lead to a high reliability and robustness of the total system.
- Standardized gear boxes and motors with outer diameters of 10 mm can be used as a basic structure for modification and adaptation regarding mechanical structure as well as materials. By this availability can be assured, costs can be decreased.
- Limit switches for avoiding a hard stop with the related risk of damaged subparts are not required anymore. A lower number of subparts leads to an increase of MTBF of the total system.
- The self-locking behaviour of the Micro Harmonic Drive gear rack helps maintaining an adjusted position of the lens especially during phases of operation with high external shocks and vibrations (e. g. during launch phase).

The following chapters describe the development efforts of a transfer of the chosen design concept to a first prototype with properties conform to the demanded specifications.

4 REALISATION

4.1 Configuration of Micro Harmonic Drive gear system

The need for low outgassing behaviour of the drive chain on the one hand and for a smooth motion with a minimized loss of precision caused by stick slip effects on the other goes along with an intensive investigation regarding the proper lubrication. Therefore the specific gear wheels of the Micro Harmonic Drive gear system (Fig. 1) as a core element of the drive chain had to be regarded at first.

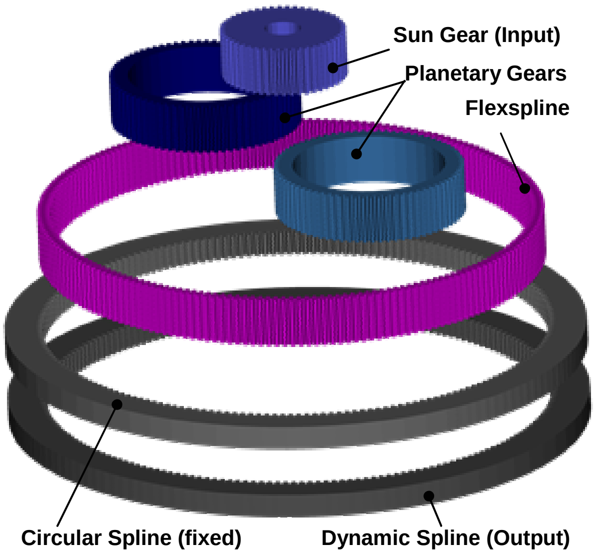

Figure 1. Component setup of a Micro Harmonic Drive gear rack.

In order to achieve the demanded property flexspline and planetary gear wheels have been covered with modified WS_2 in lamellar configuration (DICRONITE) whereas Circular Spline, Dynamic Spline, and sun gear wheel have been sputtered with MoS_2. The resulting deviation in structural thickness of the WS_2 configured gear wheels had to be compensated by a negative offset value in the gear wheel design. By this the preload of the flexspline generated by the wave generator (sun and planetary gear wheels) could be kept constant and so characteristic values such as friction torque or lost motion.

Fig. 2 to 4 describe critical structural details in the area of tooth engagement between planetary gear wheels, flexspline and circular spline respectively dynamic spline.

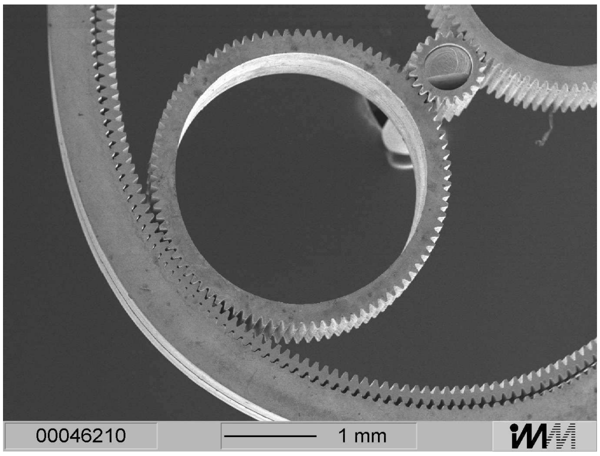

Figure 2. Assembled Micro Harmonic Drive gear rack (SEM).

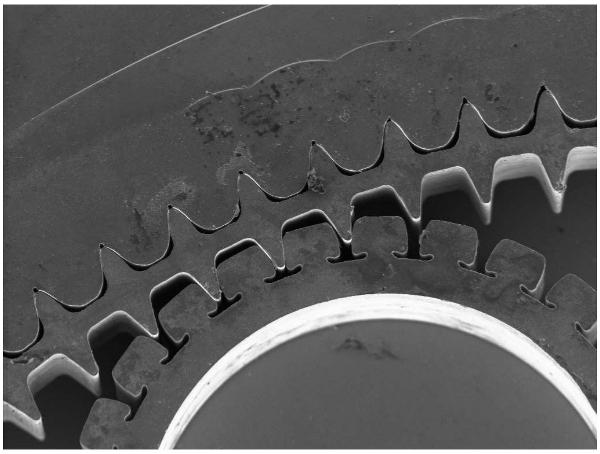

Figure 3. Focus on tooth engagement area of an assembled Micro Harmonic Drive gear rack (SEM).

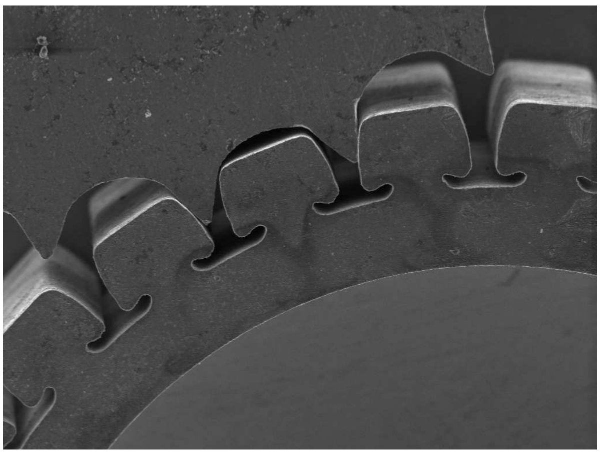

Figure 4. Structural details (P-tooth profile) of an assembled Micro Harmonic Drive gear rack (SEM).

4.2 Setup of housing, interfaces and bearings

Convenient design as well as advised choice of material for interfaces and bearings of an encapsulated, space compatible micro gear box is essential, too. Gas cavities have to be avoided, bearings have to be lubricated properly for an optimized outgassing behaviour. But still available space has to be respected. So for the developed prototype the Micro Harmonic Drive gear box has been set up with hollow input and output shaft to relieve evacuation of the unit. The stepper motor has been placed parallel to the gear box to achieve a more compact design. Materials have been chosen according to Tab.1, the mechanical setup is described in Fig. 5.

Table 1. Material list.

component	***material***
housing	1.4305 stainless steel
hollow input and output shaft	1.4305 stainless steel
subparts	1.4305 stainless steel
preloaded ball bearings	X65Cr13 high-alloy steel with MoS_2 , dry coated
micro gear wheels	electroplated NiFe, corrosion resistant
joining	2K epoxy adhesive

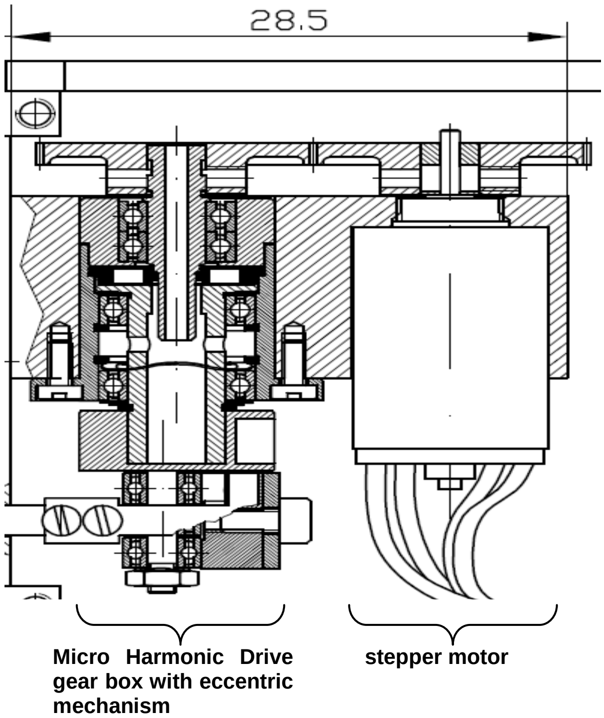

Figure 5. Mechanical setup of drive chain for linear motion of optical lens.

4.3 Configuration of stepper motor

In contrast to the standard configuration of the stepper motor type AM1020 (PRECIstep S.A.) with ball bearings (stainless steel) the lubrication has been changed from synthetic diester to WS_2 . By this minimum in modification the requested demand of availability of subparts in combination with optimized size has been covered. Nevertheless a change to a stepper motor of type VSS19 (Phytron Elektronik GmbH) has already been taken into account for further developments related to this project by reason of the topics behaviour at deep temperatures as well as outgassing behaviour.

5 EVALUATION

5.1 Influence of Lubricant

In order to confirm the decision for using WS_2 as lubricant for selective gear wheels of the Micro Harmonic Drive gear rack two different tests have been driven:

a) Measurement of life time as a function of different types of space compatible lubricant (ref. to fig. 6).

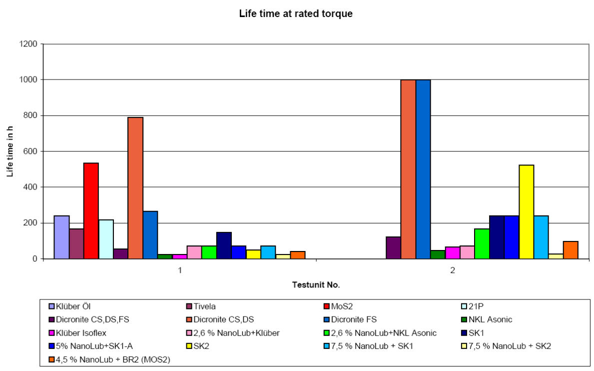

Figure 6. Results of life time test of Micro Harmonic Drive gear racks configured with different lubricants. CS - circular spline, DS - dynamic spline, FS - flexspline.

As a result life time varied significantly with the type of lubricant and - in case gear wheels could be configured separately - with the choice of gear wheel to be configured. In summary best life time performance can be expected by covering flexspline and planetary gears with WS_2 in lamellar configuration (DICRONITE).

b) Measurement of hysteresis losses as a function of different gear wheel configurations with lamellar WS_2 (ref. to fig. 7).

The hysteresis loss of a Harmonic Drive gear system is a criterion of quality in respect of the transmission function. Although dry coating in most cases goes along with an increase of hysteresis losses those losses should be minimized at least.

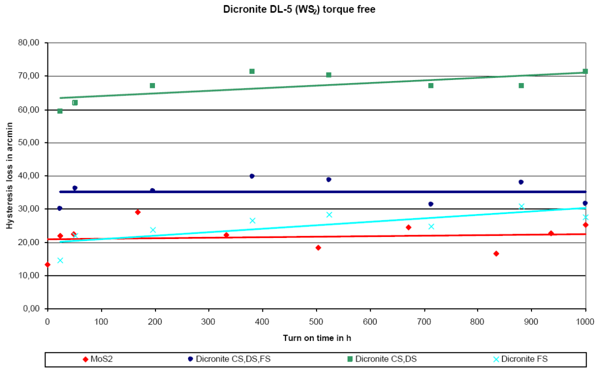

Figure 7. Results of life time test of Micro Harmonic Drive gear racks with different WS_2 configurations. CS - circular spline, DS - dynamic spline, FS - flexspline.

As a result the conclusion based on the life time test could be proved: By covering only flexspline and planetary gears with WS_2 hysteris losses achieved a minimum value.

5.2 Outgassing behaviour

To determine the outgassing behaviour of the pure motor gear unit it has been placed into a vacuum chamber. After an evacuation and outbake phase of 85 hours an end pressure of $1 \cdot 10^{-10}$ mbar could be achieved. By activating the stepper motor and tracing the vacuum chamber's internal pressure for 42 days pressure value turned into the range of $1 \cdot 10^{-9}$ mbar (ref. to fig. 8).

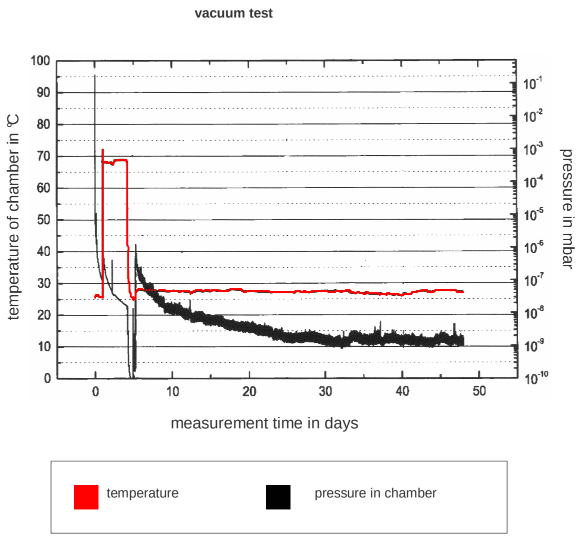

Figure 8. Chronological sequence of temperature and pressure during vacuum test.

5.3 Behaviour at deep temperatures

To determine the behaviour of the pure motor gear unit at deep temperatures it has been cooled down to an end temperature of -183°C followed by an activation of the unit. As a result all functional tests of the unit have been passed successfully.

6 RÉSUMÉ AND OUTLOOK

Based on the experiences of the driven tests, a design concept with an eccentric mechanism for transformation of rotary to linear motion as well as a modular setup of a Micro Harmonic Drive gear system a compact, space suitable and light weight micro actuator could be realized to perform a precise linear motion of an optical lens for focusing purpose (fig. 9 and 10). By this concept a positioning resolution of < 2.5 µm could be achieved at full step mode. The demands on available space could be fulfilled in most instances by overall dimensions of the camera module 96 mm x 40 mm x 19 mm. UHV capability for pressures in the range of $1 \cdot 10^{-9}$ mbar and suitability for deep temperature down to -183°C have been verified.

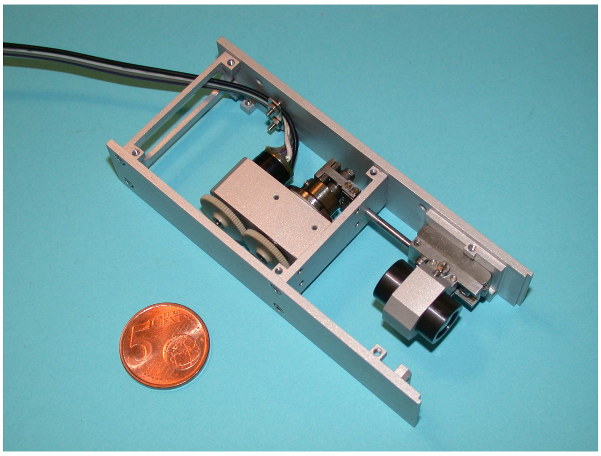

Figure 9. Mechanical structure of the camera module's drive chain.

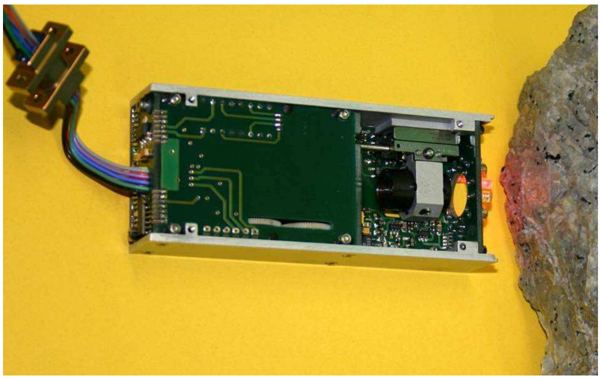

Figure 10. Complete setup of the camera module including electronics.

As an outlook for further developments on the field of space and vacuum the experiences of the described project have already been transmitted to other applications where comparable environmental conditions have to be managed. So the drive has been optimized once again by combining a stepper motor of Phytron Elektronik GmbH with a Micro Harmonic Drive gear box in order to achieve a UHV compatibility with pressures down to $1 \cdot 10^{-11}$ mbar and a positioning resolution of < 13 arcsec (fig. 11).

Figure 11. Redesign of a UHV compatible Micro Harmonic Drive system.