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FLEXURE HINGE-BASED LENS MANIPULATORS – A CONCEPT SURVEY

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ABSTRACT

A typical, but still challenging application of compliant mechanisms with flexure hinges are lens manipulators. Especially in high precision optical systems those are common means to correct optical imaging errors. The requirements for lens manipulators with respect to the resolution of motion are in the order of nanometres and nanoradians. The kinematic concepts and embodiment considerations of manipulators are proprietary knowledge of the companies using them and there is almost no literature about general design considerations available. However, general kinematic principles can be found in patents and used to compare their underlying compliant mechanisms. Therefore, this paper presents a survey of certain kinematic manipulator concepts based on existing patents. The resolution and range of motion of the manipulators are estimated and put into perspective in the context of lens manipulation. The comparison of identified kinematic concepts is used to emphasize aspects of practical implementation and embodiment design of flexure hinges in lens manipulators. The findings are discussed with respect to the bending-torsion-stiffness ratio of flexure hinges and compliant mechanisms.

Index Terms – Lens manipulator, compliant mechanism, flexure hinge, kinematic concept, opto-mechanics

1. INTRODUCTION

Compliant mechanisms or flexure hinges described in literature are often designed and optimized for different tasks, i.e. objectives and constraints. Since objectives and constraints are different, the resulting mechanisms are - despite using similar approaches and models - difficult to compare and it is almost impossible to derive general conclusions about designing compliant mechanisms the individual hinges from those.

This contribution compares monolithic flexure hinge-based lens manipulators used in optical systems – in the following simply called manipulators. Manipulators are common means to correct optical imaging errors or so-called optical aberrations – especially for high precision optical systems (HPOS), e.g. [1-3]. Since they are similar in task, objectives and constraints – those of HPOS – they will be compared to derive common requirements for compliant mechanisms and/or flexure hinges.

The scope is limited here to planar stages, i.e. flexure-based manipulators for macroscopic[1] optics moving optical elements of HPOS. The manipulators are discussed focussing on their application in objective lenses, however the application and conclusions are not limited to those.

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[1] The term “macroscopic” refers to optical elements in the order of magnitude of cm; usually in the range of 25 to 100 mm of diameter.

Flexure-based manipulators are used since the beginning of the nineties (compare publication date of [4]) and can be assumed an ongoing subject of optimisation (concluded from publication date, e.g. [5,6]).

Since manipulators are proprietary knowledge of the companies using them, there is almost no literature about their kinematic concepts or design considerations available. However, the kinematic concepts can be derived from patents.

Since the manipulators presented in this paper are exclusively taken from patents, the survey is not claimed to be complete. Thereby no distinction is made whether the patents have been granted or are still active. Furthermore, the description in patents does not contain any dimensions like lengths or diameters etc., so that the quantified parameters are not claimed to be the real ones but are estimated for the sake of comparison only.

The research questions addressed in this paper are:

- *Which kinds of general concepts of manipulators can be identified?*
- *Which kinematic properties of manipulators can be derived by the dimensional proportions represented in the patents (using embodiment assumptions)?*
- *Which general requirements for flexure hinges or compliant mechanisms can be derived from that manipulator kinematics?*

2. APPLICATION AREA OF LENS MANIPULATORS

Optical systems in general are arrangements of optical elements. The performance of an optical system, the optical imaging, is characterized by assessing the image quality. HPOS refer to optical systems with small aberrations of the optical image, i.e. diffraction limited performance/wave front errors in the sub-wavelength range[2].

In the context of wave front errors, the term “small” is usually defined by Zernike polynomials and measured in fractions of the wavelength λ utilized. Usually those aberrations amount to only “a few” mλ.[3] Decreasing wavelengths, i.e. deep ultra-violet (DUV) light and extreme ultra-violet (EUV) light, as well as higher Strehl-ratios (S → 1) result in optical aberrations in the scale of a few nm or below [7-9]. The optical aberrations are determined by:

- the quality of the optically functional surfaces,
- the homogeneity of the optical media and
- the position of the optical surfaces (i.e. the elements) relative to each other.

From a mechanical point of view, the term HPOS itself is more difficult to define, since the magnitude of the aberrations correlates – among others – with the dimensions of the lenses as well. Furthermore, technological progress shifts the boundaries from time to time. Based on references [10-12] optical systems with requirements for single lens elements with position tolerances below 0.1" and 1 µm with respect to the optical axis[4] of the objective system are regarded as HPOS. These values are regarded as the limit of an economical production at the time of writing and therefore require a system correction – i.e. manipulators - to compensate for the impact of remaining manufacturing inaccuracies (Figure 1), i.e. optical aberrations.

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[2] Wave front is one performance parameter, others are like focal length, distortion, transmission length etc. could be affected by manipulators as well. Nevertheless, for simplicity reason the effects of manipulators will be discussed using wave front errors.

[3] The dimension mλ is used in different manners. It could refer to the wavelength of a light source used for measurement of a surface or to the wavelength of the application. Here the application is used as reference.

[4] The regression line between the centres of curvature of different surfaces of the lenses is assumed to be the optical axis of an objective lens in this contribution. The fact, that this line changes during the assembly and that the definition of an optical axis is more complex for aspherical or catadioptric systems as well as differing requirements and sensitivities of individual optical elements in HPOS, is not discussed here for the sake of simplification.

These HPOS are common in semiconductor industry for lithography and inspection, in particular the objective lenses which will be the main scope of this contribution. Objective lenses in this application area have typical dimensions of up to metres in length and ≥ 10 cm in diameter. Therefore, manipulators are macroscopic systems enabling resolutions of motion in the range of (a few) nanometres or below.

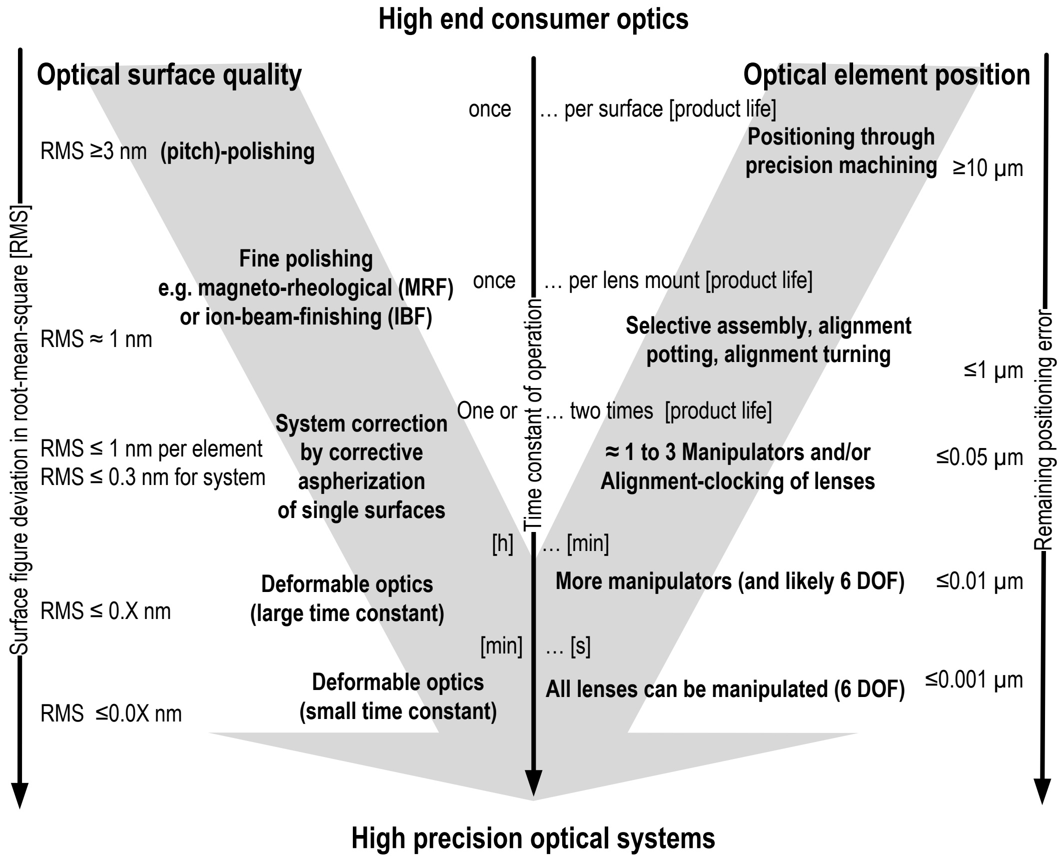

Figure 1. Overview of correction and adjustment measures for different classes of performance optics.

3. PURPOSE OF LENS MANIPULATORS

Different means and technologies (see Figure 1) are used to minimize optical aberrations and improve image quality during production and assembly of an objective lens. Figure 2 gives an exemplary overview of processes and means of system correction during the objective lens assembly and application.

Each lens element of an objective lens contributes to many optical aberrations – with a different sensitivity per lens and aberration [13]. The purpose of a manipulator is therefore:

- to translate, rotate (or even bend) individual or distinct groups of optical elements,
- in relation to other lenses of the objective lens and
- in one or more DOF,

to generate aberrations which compensate for intrinsic aberrations of the objective lens.

Consequently, often more than one manipulator is used in an objective lens. Usually many manipulators are forming cascaded and interlinked adjustment circuits inherently correcting the aberrations caused by the adjustment itself. Due to their response time and flexibility, manipulators can be used without disassembling the lens again. Furthermore, manipulators are suitable for both, system adjustment as well as for control loops in e.g. active optical systems.

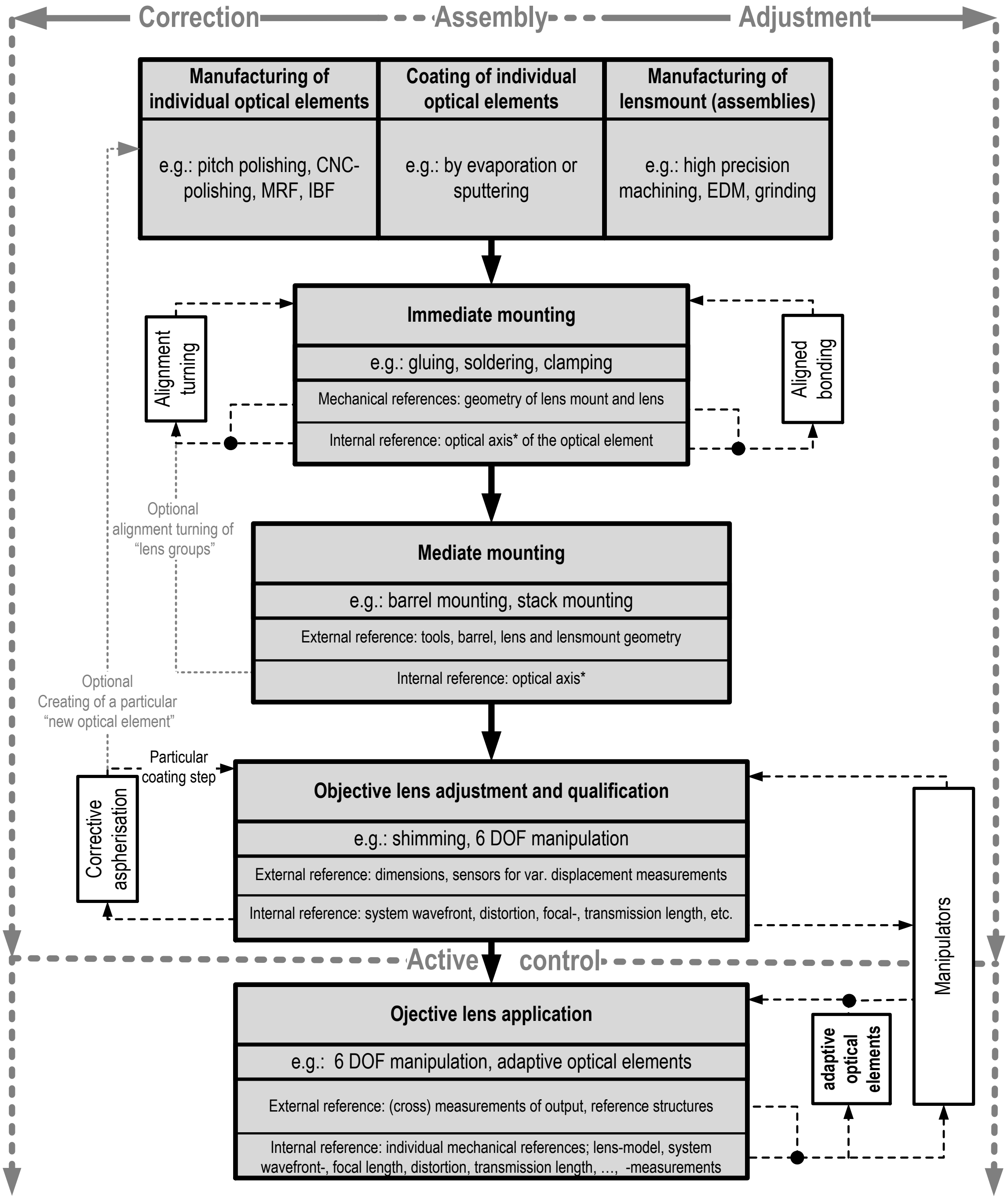

Figure 2. Overview of an alignment process of an objective lens. Adjustment and correction processes are pointed out separately. Note: The manipulators can also be used for active control during application. (*) optical axis is changing ("growing") during assembly.

4. GENERAL CONCEPTS OF LENS MANIPULATORS

Classical concepts for radial displacements of lenses are double eccentric rings [14,15] or lateral shifting by screws [16,17]. These are using sliding friction contacts between the reference and the motion part. Such contacts hardly allow resolutions[5] below 3 µm, which is out of scope for

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[5] Nevertheless, with impulse actuation considerably lower resolutions can be achieved [10].

HPOS. Therefore, manipulators for HPOS are in general flexure hinge-based to eliminate non-linear kinematic behaviour and hysteresis e.g. due to friction.

Beside the distinction in friction or flexure-based, manipulators can also be classified from a kinematic point of view. Three main classes of manipulators can be distinguished:

1. XY-manipulators (the scope of this paper), which move the optical element laterally/normal to the optical axis, e.g. to correct for asymmetric image aberrations like coma and asymmetric astigmatism [13].
2. Z-manipulators (e.g. [18-20]), which move optical elements along the optical axis, e.g. to correct for symmetric image aberrations (e.g. spherical aberration), or symmetric field dependencies, such as field curvature [13].
3. Manipulators, which allow manipulation of optical elements in all six degrees of freedom (DOF), e.g. [21,22]. This type is not including the serial combination of the first two manipulator types mentioned.

If used in an active control loop, manipulators are forming mechatronic positioning systems. The actuators/drives in such a system could be every kind of actuator. Obvious choices are piezo-drives, voice coil-actuators or just screws driven by an external tool. The motion part ("stage") of this system is the lens/intermediate lens-mount itself, while the manipulator kinematic integrates guiding and "power transmission" functionalities since it has a transmission ratio.

Nevertheless it should be mentioned that compliant manipulator kinematics, can be realized as monolithic elements or by complex assemblies of different parts. The reasons for the latter will not be discussed in this paper, however this aspect is contributing to the distinction of different transmission stages shown in Figure 4.

4.1 General concepts of XY-manipulators

The baseline for a XY-manipulator is a shifted (inner) part and an (outer) part considered to be the reference, fixed to other lenses of the HPOS during shifting. Both parts are connected via a planar kinematic utilizing flexure-hinges. The "plane" is to be perpendicular to the optical axis.

The kinematic is defining (virtual) instantaneous centres (IC) of rotation and the introduced forces/motions at decent hinges lead to a rotation about those "virtual" ICs. The position of the ICs is determined by the arrangement of kinematic sub-structures[6] – further on called manipulator kinematic [23,24]. Via the ICs the axis of motion of the manipulator can be identified. For example, drive #10 is moving the lens around IC 12 in Figure 3a and lens around IC 23 in Figure 3b.

It can be stated that there are two main arrangements of kinematics/drives described in the patents regarded for this survey (Figure 3a and 3b):

a) 2 x 90°: with two drives and manipulator kinematics and one (passive) link and
b) 3 x 120°: with three drives and manipulator kinematics without a passive link.

While it is very likely that these arrangement angles are only preferred ones, they have some certain properties. It can be seen, that[7] the kinematic structure is (almost) axial symmetric for a) and rotationally symmetric for b). This gives (for small motion ranges) perpendicular axis of motion for a) while those of b) are non-perpendicular. To move the lens in X/Y a linear combination of vectors is needed. However, taking advantage of the linear combinations and inherent over-constraints (two axes, three drives) of the 3 x 120° case, this arrangement allows slightly larger motion ranges compared to the 2 x 90° case.

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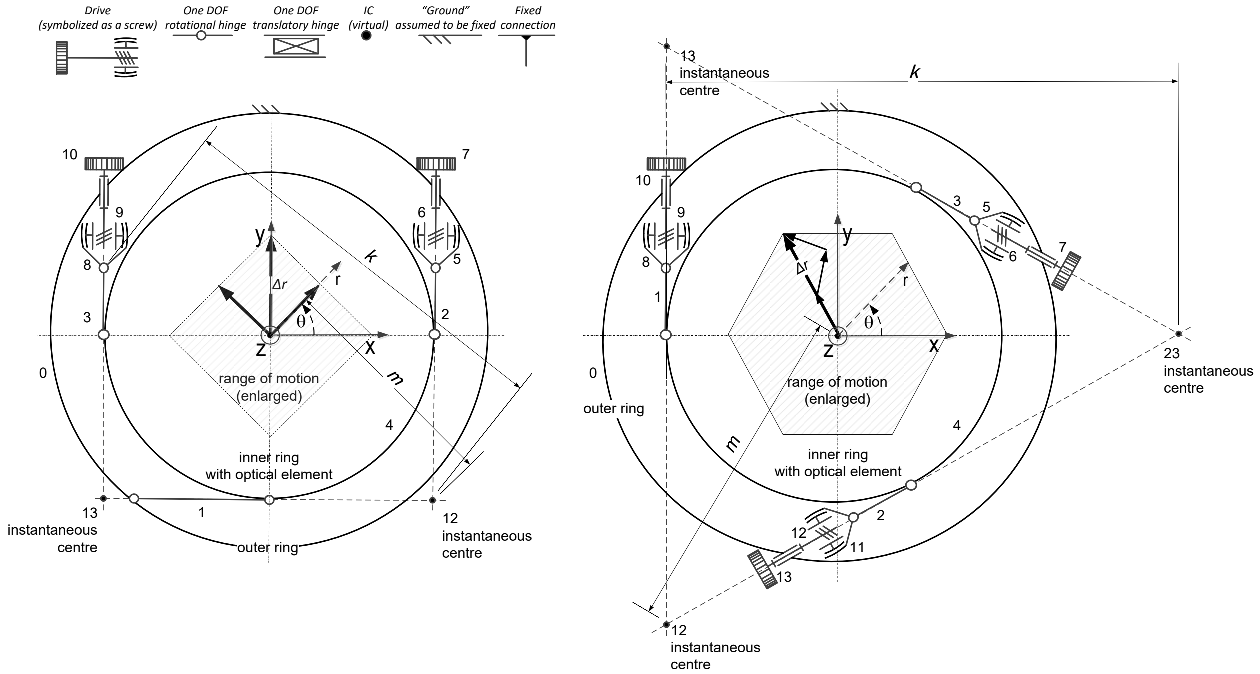
[6] Since motion ranges are small it is assumed that IC will not change (significantly) during the usage of manipulators.

[7] Furthermore, due to the location of the instantaneous centers, the kinematics can rotate the optical element slightly around the Z-axis (θ_z). This is neglected for the classification since $r/m \geq 100$ for all cases regarded.



(a) (b)

Figure 3. Two basic arrangements of lens manipulators: (a) 2 x 90° arrangement with two drives; (b) 3 x 120° arrangement with three drives. The drives are represented by screws.

4.2 Influence of the instantaneous centre location

The location of the ICs determines the range and the resolution of the kinematic structure of the manipulator by:

- the distance *k* between the point of application of motion by the drive and the related IC
- the distance *m* between the centre of the lens and the related IC.

The absolute value *k* could be different for any direction[8], however for having similar resolutions or ranges in different directions a symmetric design is needed. The value *m* determines the cosine contribution of the circular motion around the IC. The related "deviation from straightness" is a very small, second order effect (e.g. $m = 1$ cm and $r = 1$ µm results in 1 nm offset perpendicular to *r,* which could be ignored or if needed compensated with the remaining axis in an iterative process). The ratio of $u \sim k/m$ defines an "arrangement-transmission ratio". This ratio is different for the 3 x 120° and 2 x 90° arrangements of the same manipulator (sub-)kinematic but independent from scaling of the kinematic. Consequentially The arrangement-transmission ratio *u* can be understood to be the result of three reduction stages of a manipulator: the drive itself, the manipulator kinematic and the arrangement of the latter (see Figure 4). The serial combination of these stages of transmission ratios allows very small displacements.

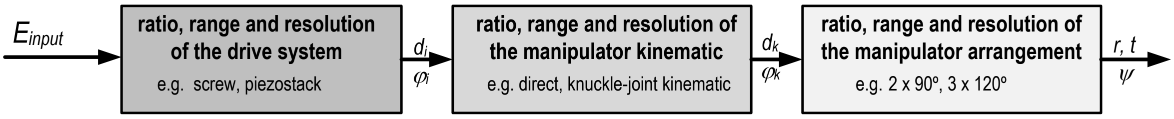


Figure 4. Contributions to the transmission ratio and therewith to the motion range and resolution of a lens manipulator, with: d_i, φ_i …linear or rotational motion of the drive system, d_k, φ_k …linear or rotational motion of the manipulator kinematic, *t*, *r*, ψ …tangential or radial motion or rotation of the lens.

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[8] The hinges 1, 2, 3 are assumed to be tangentially orientated to the inner ring, other – possible – design options are not discussed in this work.

4.3 Preliminary conclusion

So far, various aspects of the application as well as the basic structure of manipulators have been discussed. Based on this, manipulators can be distinguished by:

- DOF, e.g. two, three or more as well as the kind of DOF,
- type of friction, e.g. sliding friction or flexure-based compliant mechanisms,
- orientation of the different axis of motion, e.g. perpendicular or non-perpendicular to each other,
- symmetry of arrangement, e.g. symmetric or non-symmetric arrangements and central- or axis symmetry and
- type of actuation, e.g. actuator or driven by hand/screw.

Hereinafter, manipulator kinematics of compliant monolithic XY-manipulators for adjustments (not continuous control), actuated by screws are the main scope of this contribution and will be regarded in more detail.

5. CLASSIFICATION OF MANIPULATOR KINEMATIC CONCEPTS FOR PLANAR LENS MANIPULATORS

In the following, different manipulator kinematics published in patents will be investigated. The aim is to compare them by motion range and resolution. Since almost never specified with respect to dimensions and materials used, some assumptions need to be made. For the sake of comparability, the following assumptions are made:

- The motion of the manipulators is described to the centre of the lens (Z in Figure 3).
- It is assumed that m is large with respect to the desired displacement $(k/\Delta r \geq 1000)$ so that a small (neglectable) cosine error and $sin(x) \cong \tan(x) \cong x$ can be assumed.
- All manipulators are considered only to be 3 x 120° arrangements and symmetric (this is assumed even if stated differently or not specified in the patents[9] – for quantitative considerations kinematics are adapted to fit to the 3 x 120° arrangement).

With respect to the comparison of manipulator kinematics following simplifications are made:

- For the kinematic considerations the compliant mechanisms are substituted by planar rigid-body mechanisms and elements. The inherent deformability of the links and joints in compliant mechanisms [25] is ignored (if not stated differently).
- Each small-length notch-type flexure hinge is substituted by one revolute joint. Distinctive long beam-type flexure hinges with more distributed compliance (length to thickness ratio >> 10:1) are substituted by two revolute joints attached to a stiff beam in the manipulator kinematic model[10].

To quantify the properties of the different manipulator concepts the hypothetical lens with a diameter of 76 mm and an (inner) intermediate lens mount diameter of 100 mm is assumed.

5.1 Overview of basic manipulator kinematic concepts for XY-manipulators

The existing planar lens manipulators can be reduced to a few basic manipulator kinematic concepts, which are described in the following. For the sake of comparability, the manipulator kinematics schemes are simplified. In the shown manipulator kinematic schemes the same enumeration is used for every concept (e.g. guided moving element No. 4 and drive No. 1 and 2). Note, this enumeration of elements and joints might be different to those used in the figures derived from the patents and the manipulator kinematic schemes are not drawn to scale.

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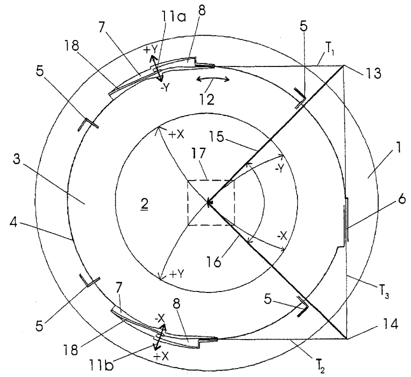
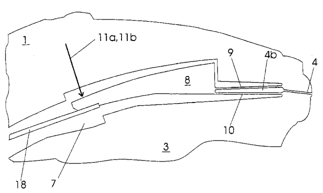
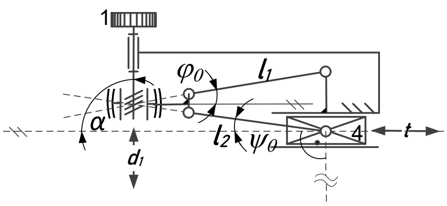
[9] Note that, to make them comparable, some kinematics are shown in a different orientation with respect to the illustration of the respective patent.

[10] See for reasoning [27,28]. Since this assumption has a big impact on the numbers of joints and links in the substitute a detailed examination of the DOFs of the substituted kinematic is omitted.

5.1.1 KIN I – Slider-crank-type manipulator kinematic

The *slider-crank-type* manipulator kinematic is, regarding the release date of the patent [4], one of the first compliant manipulator mechanisms. The illustration in the patent indicates that the manipulator kinematic is preloaded by a leaf spring (element 18 in Table 1). According to the illustration in the patent the IC of the levers l_1 and l_2 is the point where the force/motion is applied. The length of the link l_1 and l_2 are defining the transmission ratio of the manipulator (see Table 1).
Note that the instantaneous centre at the point of application of force.

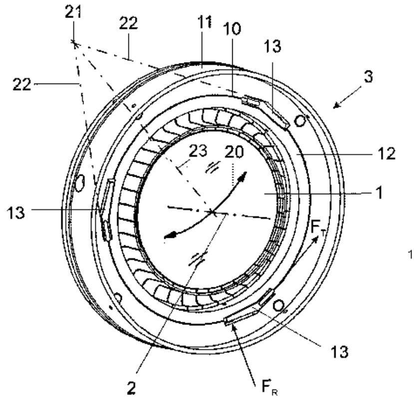
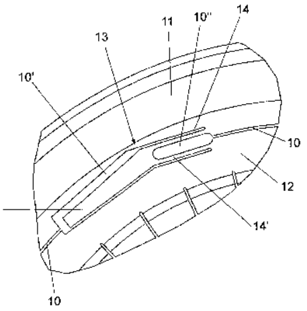
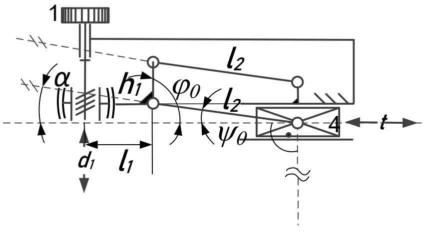
Table 1. *Slider-crank-type manipulator kinematic KIN I*

Manipulator scheme, [4]	Kinematic scheme
 	
Transmission ratio: $\Delta t \approx d_1 \cdot \left(\frac{1}{l_1}+\frac{1}{l_2}\right)$	Assumptions: $l_1 = l_2$, $\alpha = 90°$, $\psi_0 = \varphi_0$

5.1.2 KIN II – Slider-crank-type manipulator kinematic with parallel-crank mechanism

A slightly different slider-crank-type manipulator kinematic is published in [28,29]. Compared to KIN I a preloading is not indicated.

Table 2. *Slider-crank-type manipulator kinematic KIN II* with parallel-crank mechanism

Manipulator scheme [29]	Kinematic scheme
 	
Transmission ratio: $\Delta t \approx d_1 \cdot \left(\frac{h_1}{l_2}\right)$	Assumptions: $l_1 = l_2$, $\psi_0 = \alpha = \varphi_0 \rightarrow 0$, $h_1 < l_1$

Albeit quite similar to KIN I, the levers l_1 and l_2 are not pointing to the point where the force is applied and are shown to be parallel. If the stiffness of the joints forming the instantaneous centres is much higher compared to the parallel levers, the translation results only from the ratio h_1/l_1 (see Table 2). There might be a contribution from a parallel shift which is creating a (cosine) contribution which might be the reason why the angle α is not shown (and assumed for this work) to be 0° (see [29]).

Note that this manipulator kinematic is only working due to the restoring forces of the flexure hinge.

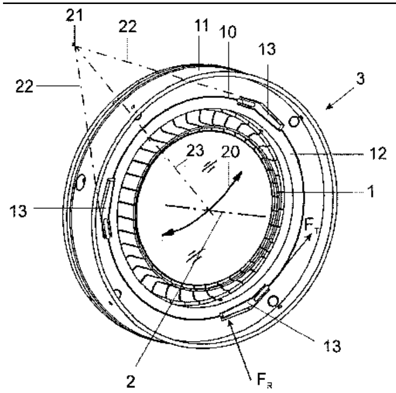
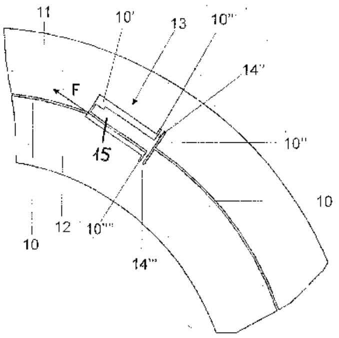
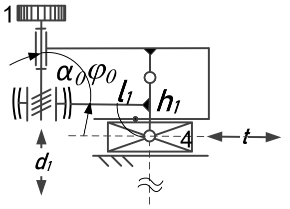
A similar manipulator kinematic concept can be found in the 6-DOF-manipulator shown in [23], where a slightly modified version is used, although the instantaneous centres consideration becomes more complex due to the distributed compliance for the different DOF.

5.1.3 KIN III – Manipulator kinematic with (radial) tension-bending link

By substituting the long flexure hinge of KIN II with only one hinge at each side, KIN III can be derived. The manipulator kinematic with a (radial) tension-bending link is the second manipulator presented in [29]. A representation via a simplified rigid-body structure is difficult since the manipulator kinematic is – assuming ideal radial orientation of the links h_1 – kinematical constrained and has no DOF (see Table 3). Thus, it works exclusively by elastic deformation (bending and tension) of the link h_1 and hinge design is important for realization of the manipulator.

Note that hinges are bending and tension/compression loaded for manipulation. It can be assumed that, due to superposition of tension and bending stress, the motion range for this manipulator kinematic is far below 2°.

Table 3. *Tension-bending link manipulator kinematic KIN III.* The manipulator in the left picture is different to the detail view, since two different manipulator kinematic concepts are shown in the patent for the 3 x 120° arrangement.

Manipulator scheme [29]	Kinematic scheme
 	
Transmission ratio: $\Delta t \approx d_1 \cdot \left(\frac{h_1}{l_2}\right)$	Assumptions: $l_1 = l_2$, $\alpha_0 = \varphi_0 \rightarrow 0$

5.1.4 KIN IV – Flipped slider-crank kinematic

A different version of the flipped slider-crank manipulator kinematic KIN IV is described in [30]. This patent shows two different manipulator arrangements. The first one of those is comparable to KIN II and differs from the latter by a "folded" link. The parameters influencing the transmission ratio are the same as in KIN II, but the sign of motion is different.

5.1.5 KIN V – Toggle-lever kinematic

The second manipulator kinematic shown in [30] is the toggle-lever manipulator kinematic KIN V (see Table 5). This is quite different to the KIN IV and gives a transmission ratio influenced by three parameters.

It must be noted that the transmission ratio is highly non-linear, resulting in extreme transmission ratios for $h \rightarrow 0$. This is likely limited in practice by manufacturing restrictions and stability concerns with respect to the manipulator kinematic reversal point. Furthermore, load changes at the screw/drive will affect the manipulator kinematic behaviour of the manipulator.

Table 4. *Flipped slider-crank-manipulator kinematic KIN IV.* Note that the manipulator in the left picture is different to the detail view, since two different manipulator kinematic concepts are shown in the patent [30].

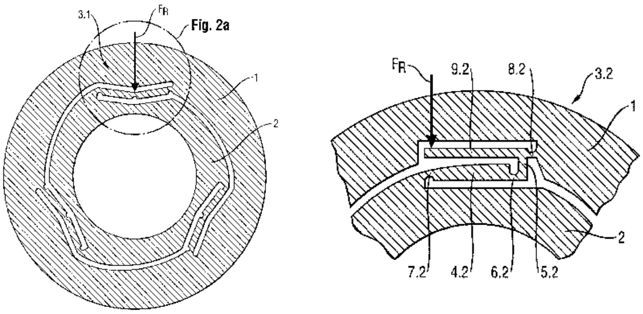
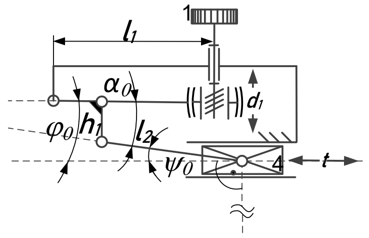
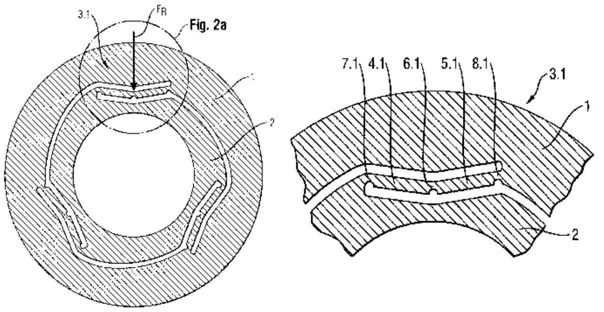
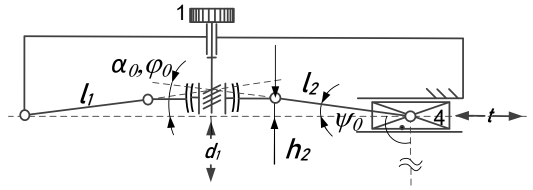
Manipulator scheme [30]	Kinematic scheme
	
Transmission ratio: $\Delta t \approx d_1 \cdot \left(\frac{-h_1}{l_2}\right)$	Assumptions: $l_1 = l_2$, $\psi_0 = \alpha_0 = \varphi_0 \rightarrow 0$

Table 5. *Toggle-lever kinematic KIN V* note that this manipulator kinematic is not applying forces to the hinge as shown in the patent.

Manipulator scheme [30]	Kinematic scheme
	
Transmission ratio: $\Delta t \approx d_1 \cdot \left(\frac{h_2}{l_1} + \frac{h_2}{l_2}\right)$	Assumptions: $l_1 = l_2$, $\psi_0 = \alpha_0 = \varphi_0 \neq 0$, $h_2 \ll l_1$

5.1.6 KIN VI – Manipulator kinematic with a compliant coupling to an external drive

A very simple coupling of the inner ring of a lens mount for a manipulator using IC and flexure hinge is shown in [31], (see Table 6). The coupling of the drive itself is part of the compliant mechanism. The manipulator kinematic transmission ratio is $\Delta t/\Delta a = 1$, so only the drive element and the arrangement determine the transmission ratio of the kinematic.

It should be noted that the drive unit has a guiding function as well. So clearance/preload of the mechanism (despite not regarded for the further considerations) will influence the kinematic behaviour.

5.1.7 KIN VII – Combined toggle-lever/slider-crank kinematic

The toggle-lever/slider-crank manipulator kinematic combining aspects of KIN IV and KIN V resulting in a complex mechanism presented in [32]. This – especially in the 3 x 120° arrangement – highly over-constraint (i.e. six screws for two translations and one rotation) arrangement provides two different transmission ratios (Table 7). This is, according to the patent description, intended to work as a coarse- and fine-drive.

It must be emphasized that depending on the angle α and β the instantaneous centres for coarse and fine motion might be different, which results in different directions of motion for the coarse and the fine drive.

Note that the toggle-lever manipulator kinematic forms the fine drive and is also actuated by the slider-crank kinematic.

Table 6. *Compliant coupling manipulator kinematic KIN VI.* The thread is shown in a rotational joint, since an angular compensation (axis of rotation perpendicular to the image plane) is assumed to be possible, i.e. due to clearance in the thread or low stiffness of adhesive bond to an actuator e.g. piezo.

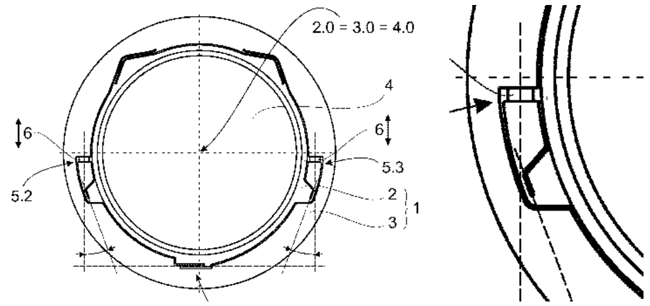
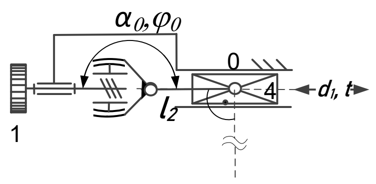
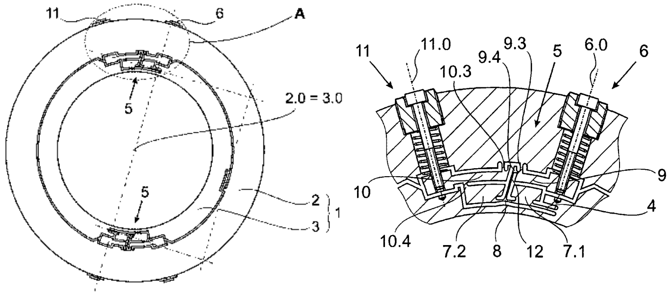
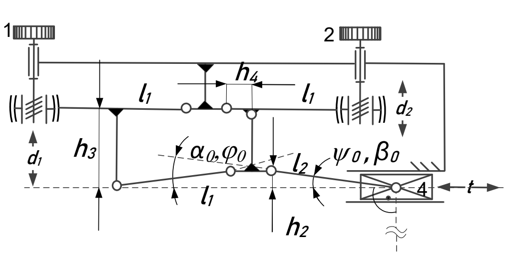
Manipulator scheme [31]	Kinematic scheme
	
Transmission ratio: $\Delta t = d_1$	Assumptions: $a_0 = \varphi_0 = 180°$, d_1… drive motion

Table 7. *Combined toggle-lever/slider-crank manipulator kinematic KIN VII*

Manipulator scheme [32]	Kinematic scheme
	
Transmission ratio (coarse drive): $\Delta t_\mathrm{c} \approx d_1 \cdot \left(\frac{-h_3}{l_2}\right)$ Transmission ratio (fine drive): $\Delta t_\mathrm{f} \approx d_2 \cdot \frac{h_4}{l_1} \cdot \left(\frac{h_2}{l_1} + \frac{h_2}{l_2}\right)$	Assumptions: $l_1 = l_2 = 1$, $h_4 << l_1$, $h_4 < l_3$, $h_4 \approx h_2$, $\alpha_0 = \varphi_0 = \psi_0 \neq 0°$

5.1.8 KIN VIII – Folded slider-crank manipulator kinematic

KIN VIII [6] is another slider-crank manipulator kinematic comparable to KIN IV. It is a folded slider-crank manipulator kinematic with the link l_2 "folded outwards” (see Table 8). According to the description, the purpose for this is to have the flexure hinges as far outside as possible to the inner and the outer ring.

5.1.9 Summary of kinematic concepts for XY-Manipulators

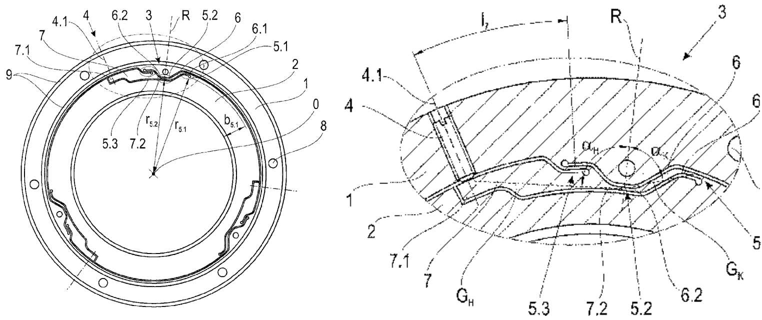
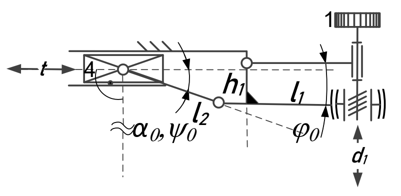
From the patents reviewed, all manipulators beside KIN III make use of (obvious) ICs and can be considered as classical kinematic structures realized with flexure hinges with concentrated compliance. Most of the kinematics are based on either slider-crank or toggle-lever four-link kinematics. The exceptions KIN III, VI and VII are different with respect to:

- KIN III: ICs are not clear,

- KIN VI: Is not a “true” kinematic since the thread of the screw (or any other drive) is used for guiding as well. A 3 x 120° arrangement needs an additional guidance of the lever l_2 as presented in [33].
- KIN VII: Is a nested combination of toggle-lever and slider-crank kinematic.

Due to the small range of motion and the similarities of the arrangement, similar kinematic properties can be assumed. For the sake of the comparison of their behaviour, the described kinematics will be quantified in the next section.

Table 8. *Folded slider-crank manipulator kinematic KIN VIII*

Manipulator scheme [6]	Kinematic scheme
	
Transmission ratio: $\Delta t \approx d_1 \cdot \left(\frac{h_1}{l_1}\right)$	Assumptions: $l_1 = l_2$, $\psi_0 = \alpha_0 = \varphi_0 \rightarrow 0$

5.2 Comparison of the kinematic properties for selected XY-manipulators

To have a functional baseline requirement, the needed adjustment range R for a planar lens manipulator should be estimated. Therefore, it is assumed that the statistically distributed decentration of all lenses including the manipulator is compensated by an intentional single decentration (peak to valley, P-V). A number of n lenses with a radial misalignment of r_i for each lens i after the assembly results in R[11] acc. Eq. 1.

$$R = 5 \cdot \sqrt{\sum_{i=1}^{n} (r_i)^2} \tag{1}$$

For an objective lens with nine lenses (e.g. as shown in [7]) and radial misalignment with respect to the optical axis of 1 µm to 2 µm (see [10,11,34]) after assembly results in ±15 µm or ±30 µm P-V radial displacement necessary for an individual lens element and thus as the required functional range of the lens manipulator. These numbers refer to the optical axis/lens vertices and are not taking any mechanical tolerances of the manipulator itself into account.

The manipulator kinematics mentioned above are scaled to them comparable. For the quantitative comparison of the manipulator kinematics, some more assumptions are made as well:

- A maximum rotational deflection of 2° of the most strongly deflected flexure hinges[12] (different deflection angles are to be expected in the different hinges in the compliant mechanism) is assumed to be acceptable (see [35]).
- To determine transmission ratio, motion range and (minimal) resolution a 3 x 120° arrangement is assumed.
- The motion range is determined with the largest possible vector addition of the latter.

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[11] For this estimation it is assumed that a single P-V displacement compensates for the RMS of aberrations of all other lenses. The ratio of P-V to RMS is not a fixed quantity and depends on type of and distribution of errors in an objective lens. For the translation of RMS error of multiple lenses of an objective lens into a P-V shift of a particular lens, a rule of thumb for small, smooth, random errors (P-V≈ 5x RMS) [35,36] is used in this paper.

[12] For each manipulator kinematic a different hinge can be critical.

Based on a reasonable optical element of 76 mm diameter (see [7,11]), some design parameters for the different kinematics were estimated by scaling using the images in the patents. In addition, two different use cases, i.e. screw pitches for a M2 and a M3 screw, are considered. A sensitivity of 1 mm at the circumference of a tool like a screwdriver of 32 mm diameter is assumed, which translates to minimal turn of the screw of ≈ 3°. Using these assumptions, the values shown in Table 9 and Table 10 can be obtained.

Note that the ranges for the drive of use-case 1 and 2 are different due to the chosen dimensions and maximum rotational deflection of 2°. The ranges do not depend on the chosen screw (albeit the allowed number of their turns does).

Albeit the numbers for resolution or range are defined by the chosen dimensions as well as by the assumed maximal angle of hinge deflection of 2°, it can be shown that a resolution of 200 nm and a range of ±100 µm are possible. Transmission ratios of 1:2000 up to 1:87000 can be achieved by the manipulators with the exemplarily chosen dimensions (see Table 9). The normalized (to the pitch of the driving screw) range/resolution-ratio is very similar for all manipulator concepts (see Table 10). The only runaways are the mentioned exemptions KIN III, VI and VII.

Table 9. Quantitative comparison of the manipulator kinematics derived from the patents. Two different use cases, assuming two different sets of dimensions and drives, are shown.

Drive assumption	Use-case 1/assumptions			Use-case 2/assumptions		
	Screw-driven (M3): 0.5 mm pitch p_D → 0.5 mm range r_D			Screw-driven (M2): 0.4 mm pitch p_D → 0.7 mm range r_D		
exemplarily chosen dimensions	l_1 [mm]		14.5	l_1 [mm]		20
	l_2 [mm]		10	l_2 [mm]		11
	h_1 [mm]		2	h_1 [mm]		1.5
	h_2 [mm]		0.7	h_2 [mm]		0.6
	h_3 [mm]		4	h_3 [mm]		4.5
	h_4 [mm]		0.5	h_4 [mm]		0.4
Parameters	Resolution Δr [nm]	Range r [µm]	Transmission ratio u [-]	Resolution Δr [nm]	Range r [µm]	Transmission ratio u [-]
KIN I	365	92	2742	212	69	4728
KIN II	365	92	2742	159	69	6304
KIN III	365	92*	2742	159	69*	6304
KIN IV	365	92	2472	159	69	6304
KIN V	255**	24	3917	127**	17	7879
KIN VI	2644	667	378	2115	920	473
KIN VII (coarse)	729	184	1371	476	207	2101
KIN VII (fine)	36**	3.4	27420	12**	1.9	86674
KIN VIII	201	47	4970	71	28	14008

* *It is doubtful that the manipulator will achieve such a range since the hinge is tension and bending loaded and hence these values should be regarded as hypothetical*

** *The kinematic behaviour of this manipulator kinematic is non-linear and close to the stretched position the resolution becomes almost infinite. Therefore, values for the outmost position are listed.*

For the kinematics concerned, the transmission ratio and thus the resolution and range of the manipulators are determined by the chosen dimensions. However, the ratio of resolution and range is not affected by changes of dimensions but determined by the 2° limit.

Geometric changes, e.g. towards smaller values of resolutions will lead to a proportional decrease in range. With respect to the estimation above of necessary 15 µm to 30 µm range it can be assumed that resolutions of 60 to 30 nm can be achieved by flexure-hinge based manipulators.

Another option to change the ratio between resolution and motion range is to select a drive system with proportional difference of resolution to range ratio – e.g. screws with a smaller pitch – which was not in scope for this survey.

Table 10. Estimated range/resolution ratios of the manipulator kinematics of regarded manipulators (same use-cases and remarks as in Table 9).

	Use-case 1		Use-case 2	
	Range/ resolution ratio	$\frac{r \cdot p_D}{\Delta r \cdot r_D \cdot 30 \cdot \pi}$	Range/ resolution ratio	$\frac{r \cdot p_D}{\Delta r \cdot r_D \cdot 30 \cdot \pi}$
KIN I	252.1	2.7	435	2.7
KIN II	252.1	2.7	435	2.7
KIN III	252.1*	2.7*	435*	2.7*
KIN IV	252.1	2.7	435	2.7
KIN V	94.2**	1**	141**	1**
KIN VI	252.1	2.7	435	2.7
KIN VII (coarse) KIN VII (fine)	252.1 94.2**	2.7 1**	435 162**	2.7 1**
KIN VIII	235	2.5	397	2.5

6. DISCUSSION AND CONCLUSIONS

Flexure hinge-based lens manipulators can achieve motion ranges and resolutions necessary to correct optical aberrations in high-precision optical systems. Based on the patent survey, it was possible to point out that 2x90° and 3x120° arrangements are the two basic arrangements of planar manipulators. Despite differences in details of the embodiment design (compare KIN I [4] and KIN II [29]), slider-crank and toggle-lever mechanisms could be found to be the dominating manipulator kinematics. Based on the images from the patents, assumptions about dimensions have been made which – with respect to the estimated requirements – resulted in reasonable manipulators with respect to the requirements estimated acc. to Eq. 1.

Albeit the dimensions were designed arbitrarily, all manipulators are very similar in terms of resolution and range of motion. Although both parameters are defined by the chosen dimensions and thus the similarities are coincidental, the relationship between the range of motion and resolution of manipulators shows a great deal of similarity for all kinematics. Therefore it can be assumed that further requirements, not regarded in this work, lead to their variety. Possible reasons can be seen in legal limitations, parasitic forces to the lens, costs/technological preferences, stability etc. Those arguments can also assumed to be relevant for the choice of arrangements.

The similarity itself results from the assumption of the maximum deflection angle of a flexure hinge to be approximately 2°. The extent to which this assumption is appropriate in all cases, e.g. for specific, mixed loads (see KIN III) of the flexure hinges, has not been examined in this paper. Due to the monolithic "closed" structure of the manipulators all hinges usually absorb bending loads as well as tensile or compressive loads. Therefore, the maximum allowable flexure hinge deflection and, therefore, the loads of a compliant mechanism are crucial for the design of compliant mechanisms.

With respect to the required high stability and ultra-precise motion of lens manipulators, the simplification to planar kinematics must be considered as critical as well. Loads with force components perpendicular to the plane of motion (and the resulting torques) can be caused by:

- gravity contribution perpendicular to plane of motion,
- forces during various life cycles (e.g. cleaning, assembly, transport, etc.),

- manufacturing tolerances of the manipulator, i.e. flexure hinges with cardinal stiffness axis and/or offset of the forces not perpendicular to the motion plane as well as torques introduced by the drives used to manipulate and
- dynamic effects and various eigenmodes of the manipulators.

The resulting torques will lead to an (nominally) inclined position of the lens and a non-level manipulator motion. The resulting tilting motions are critical with respect to the functional required stability. Consequently, the torsional stiffness of each individual flexure hinge is another important design aspect.

Since increasing of the hinge thickness to maximise the torsional stiffness results in bending-stiffer flexures as well as higher stresses during the manipulation [37,38], the bending- and torsional-stiffness of the individual flexure hinges must be considered simultaneously during the design of the compliant mechanism.

As an outcome of this survey, the bending-torsion-stiffness relation of flexure hinges is of practical relevance for kinematics like lens manipulators. However, the bending-torsion-stiffness ratio is hardly considered as a design criterion in literature. Therefore, optimised flexure hinge shapes (see [39,40]) as well as the optimisation of the (manipulator) kinematic related to the maximum strain of each hinge due to bending and torsion (see [41,42]) will be interesting topics for the future research.

REFERENCES

[1] Noll, T.; Holldack, K.; Reichardt, G.; Schwarzkopf, O.; Zeschke, T.: *Parallel kinematics for nanoscale Cartesian motions*. Precis. Eng. 2009. doi:10.1016/j.precisioneng.2008.07.001.

[2] Teo, T.J.; Yang, G.; Chen, I.-M.: *A large deflection and high payload flexure-based parallel manipulator for UV nanoimprint lithography: Part I. Modelling and analyses*. Precis. Eng. 2014. doi:10.1016/j.precisioneng.2014.05.003.

[3] Hu, R.; Liu, S.; Li, Q.: *Topology-optimization-based design method of flexures for mounting the primary mirror of a large-aperture space telescope*. Appl. Opt. 2017. doi:10.1364/AO.56.004551.

[4] Trunz, M.; Mühlbeyer, M.; Hilgers, R.; Merz, E.: *Optische Abbildungsvorrichtung, insbesondere Objektiv, mit wenigstens einem optischen Element*. German Patent DE19901295 A1, filed 15 Jan. 1999, issued 20 Jul. 2000.

[5] Trunz, M.; Mühlbeyer, M.; Hilgers, R.; Merz, E.: *Optical imaging up device comprising at least one optical element*. Japanese Patent JP4416893 B2, filed 17 Jan. 2000, issued 17 Feb. 2010.

[6] Erbe, T.; Fahr, S.: *Adjustable lens mount*. US Patent US9823437 B2, filed 29 Sep. 2016, issued 21 Nov. 2017.

[7] Fahr, S.; Werschnik, J.; Bening, M.; Baldsiefen, T.: *Prediction and validation of the polarization performance of high-numerical aperture inspection lenses*. In International Optical Design Conference 2017. International Optical Design Conference 2017, Denver, United States. 2017.

[8] Sure, T.; Bauer, T.; Heil, J.; Wesner, J.: *DUV-microscope objectives: Technology driver that forces the production to switch from the micrometer scale to the nanometer scale*. In Proc. SPIE 5965. Optical Fabrication, Testing, and Metrology II, Jena, 2005.

[9] Sondermann, M.; Scheibe, H.; Theska, R.: *Lens mounts in optical high performance systems with small diameters*. In Proceedings of the 56th International Scientific Colloquium. Ilmenau. 2011.

[10] Frank, S.: *Justierdrehen – eine Montagetechnologie für Hochleistungsoptik*. PhD-Thesis; TU Ilmenau, Ilmenau, 2011.

[11] Sondermann, M.: *Mechanische Verbindungen zum Aufbau optischer Hochleistungssysteme*. PhD-Thesis; TU Ilmenau, Ilmenau, 2011.

[12] Beier, M.: *Justierdrehen - Technologie zur Herstellung von Objektiven hoher Abbildungsqualität*. In. Tagungsband zur 6. Fachtagung „Feinwerktechnische Konstruktion". 8 November, Dresden, 2012.

[13] Gross, H.; Zügge, H.; Peschka, M.; Blechinger, F.: *Handbook of Optical Systems*. Wiley-VCH: Weinheim, Germany, 2006.

[14] Krause, W.: *Konstruktionselemente der Feinmechanik*. Hanser: München, 2004.

[15] Hage, K.: *Fassung mit Justierelementen*. German Patent DD000000278207 A1, filed 19 Dec. 1988, issued 25 Apr. 1990.

[16] Bornschein, M.: *Monolithische optische Fassung*. German Patent DE102008063223 B3, filed 23 Dec. 2008, issued 9 Sep. 2010.

[17] Frankovich, J.W.; Grejda, R.D.; Hanford, K.E.; McMichael, T.R.: *X-Y adjustable optical mount with Z rotation*. US Patent US8085482 B2, filed 27 May 2010, issued 27 Dec. 2011.

[18] Blanding, D.L.; Bruning, J.H.; Frankovich, J. W.; Hanford, K.E.; Magierski, K.J.: *Kinematic optical mount*. US Patent US7800852 B2, filed 26 June 1984, issued 6 May 1986.

[19] Becker, J.; Gellrich, B.; Lang, W.; Kohl, A.; Kraus, S.: *Vorrichtung zur Lagerung eines optischen Elementes*. German Patent DE10051706 A1, filed 18 Oct. 2000, issued 2 May 2002.

[20] Blanding, D.L.; Bruning, J.H.; Frankovich, J. W.; Hanford, K.E.; Magierski, K.J.; Sanson, M.C.: *Optical mount pivotable about a single point*. US Patent US7612956 B2, filed 27 Feb. 2008, issued 3 May 2009.

[21] Shibazaki, Y.: *Optical element holding apparatus*. US Patent US7154684 B2, filed 10 Aug. 2001, issued 26 Dec. 2006.

[22] Weber, U.; Kugler, J.: *Positioning unit and alignment device for an optical element*. US Patent US7738193 B2, filed 18 Jun. 2005, issued 15 Jun. 2010.

[23] Liu, W.; Mills, J.K.: *MEMS Remote Centre of Compliance Design*. In Proceedings of the 2006 IEEE International Conference on Mechatronics and Automation. Luoyang, China. 2006.

[24] Baitinger, H.; Latzel, M.; Nefzi, M.: *Precision flexure hinges for high-performance optics*. In Proceedings of the 6th euspen International Conference. Nottingham, UK. 2016.

[25] Linß, S.; Gräser, P.; Räder, T.; Henning, S.; Theska, R.; Zentner, L.: *Influence of geometric scaling on the elasto-kinematic properties of flexure hinges and compliant mechanisms*. Mech. Mach. Theory 2018, doi:10.1016/j.mechmachtheory.2018.03.008.

[26] Awtar, S.; Shimotsu, K.; Sen, S.: *Elastic Averaging in Flexure Mechanisms: A Three-Beam Parallelogram Flexure Case Study*. J. Mech. Des. 2010. doi:10.1115/1.4002204.

[27] Yu, Y.-Q.; Feng, Z.-L.; Xu, Q.-P.: *A pseudo-rigid-body 2R model of flexural beam in compliant mechanisms*. Mech. Mach. Theory 2012. doi:10.1016/j.mechmachtheory.2012.04.005.

[28] Rau, J.; Schöppach, A.; Weber U.: *Objective comprising at least one optical element*. European Patent EP000001577693 B1, filed 8 Feb. 2005, issued 21 Sep. 2005.

[29] Schletterer, T.: *Lateral verstellbare Fassung für optische Elemente*. German Patent DE102007030579 B4, filed 29 Jun. 2007, issued 2 Oct. 2008.

[30] Reichmann, L.; Bornschein, M.: *Lateral verstellbare optische Fassung mit Kniehebelmanipulatoreinheiten*. German Patent DE102008029161 B3, filed 19 Jun. 2008, issued 8 Oct. 2009.

[31] Bening, M.; Erbe, T. Richter, U.; Seher, B.: *Optische Baugruppe mit einer monolithischen Fassung mit in einer gleichen Richtung wirkenden Stellschrauben*. German Patent DE102013109605 B3, filed 3 Sep. 2013, issued 18 Jun. 2014.

[32] Ulbricht, O.; Erbe, T.: *Zweistufig justierbare Fassung*. German Patent DE102013018786 B3, filed 5 Nov. 2013, issued 17 Jul. 2014.

[33] Janssen Precision Engineering, *Module design: 3DOF optical motion stage*. Available online: https://www.janssenprecisionengineering.com/page/module-design-3dof-optical-motion-stage/ (accessed on 30. Oct. 2018).

[34] Beloivan, P.A.; Latyev, S.M.; Frolov, D.N.; Theska, R.: *Estimation of clearances in the design and adjustment of barrel type lens systems*. In Proceedings of the SPIE Optical Metrology. SPIE Optical Metrology, Munich, Germany. 2017.

[35] Schwertz, K.; Burge, J.: *Field Guide to Optomechanical Design and Analysis*. 2012. https://doi.org/10.1117/3.934930

[36] Shannon, R.: *The Art and Science of Optical Design*. Cambridge. Cambridge University Press. 1997. doi:10.1017/CBO9780511816529

[37] Linß, S.; Schorr, P.; Zentner, L.: *General design equations for the rotational stiffness, maximal angular deflection and rotational precision of various notch flexure hinges*. Mech. Sci. 2017, 8, 29–49, doi:10.5194/ms-8-29-2017.

[38] Zelenika, S.; Munteanu, M.G.; Bona, F. D.: *Optimized flexural hinge shapes for microsystems and high-precision applications*. Mech. Mach. Theory 2009, 44, 1826–1839, doi:10.1016/j.mechmachtheory.2009.03.007.

[39] Liu, M.; Zhan, J.; Zhu, B.; Zhang, X.: *Topology Optimization of Flexure Hinges with Distributed Stress for Flexure-Based Mechanisms*. In 2018 MARSS. 2018 International Conference on Manipulation, Automation and Robotics at Small Scales (MARSS), Nagoya, Japan, 2018.

[40] Gräser, P.; Linß, S.; Harfensteller, F.; Torres, M.; Zentner, L.; Theska, R.: *High-precision and large-stroke XY micropositioning stage based on serially arranged compliant mechanisms with flexure hinges*. Precis. Eng. 2021, 72, 469–479, doi:10.1016/j.precisioneng.2021.02.00107.

[41] Guo, K.; Ni, M.; Chen, H.; Sui, Y.: *A monolithic adjusting mechanism for optical element based on modified 6-PSS parallel mechanism*. Sensors Actuat. A-Phys. 2016, 251, 1–9, doi:10.1016/j.sna.2016.09.035.

[42] Linß, S.; Henning, S.; Zhao, C.; Erbe, T.: *The bending-torsion-stiffness ratio of flexure hinges with common and polynomial notch shapes*. In 7. IFToMM D-A-CH Konferenz. 2021, doi:10.17185/duepublico/74059.

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