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Modular kirigami arrays for distributed actuation systems in adaptive optics

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The demands on adaptive optics are increasing to achieve high performance and meet the requirements for accuracy and reliability with these systems. At present, common technologies for actuator arrays are highly developed and designed in complex arrangements leading to bulky devices. In this work, we propose a novel approach for designing modular actuation arrays by means of kirigami metasheets realigned in parallel and leveled in-plane. The study focuses on the numerical analysis of different cut patterns to couple lift-off motions within a thin, scalable sheet. A design of a modular actuation array is explained and illustrated in the context of a deformable mirror. The optimal lift-off positions within the array are calculated for this example by a proposed positioning algorithm which makes use of common methods in adaptive optics such as Zernike polynomial fitting. The algorithm is validated by several simulations calculating the membrane deflection, and the overall concept is discussed.

I. INTRODUCTION

Many engineering developments benefit from advanced structures with tunable material properties, reconfigurable shapes and versatile functions whose fundamentals are based on origami and kirigami techniques [1–3]. Years ago, the link between optical systems and origami was already established when the reverse corner fold, one of the most popular origami folds, was used for describing optical layouts and simulations of optical systems [4]. Meanwhile, novel topologies and shapes can be designed by folding and cutting surfaces [5] which has led to inventions such as ultra-low-cost foldable microscopes [6], deployable solar panels [7] and inflatable booms for space structures [8, 9]. The field of optomechanics is rapidly developing [10]. Besides optomechanical concepts for sensing of mechanical motion [11, 12] and fundamental arrays and circuits with higher modes [13, 14], actuated systems inspired by kirigami such as microscanners [15], nano-kirigami metasurfaces and metastructures for visible light manipulation and reconfigurable optical devices [16, 17] were proposed.

Adaptive optics is an advanced technique for optimizing optical systems by correcting the effects of an incoming wavefront and its added distortion. Such a technology applies, next to a wavefront sensor and computing system, an active optical element such as a deformable mirror within an imaging system to measure the optical distortion, extract the information and correct the wavefronts by shaping the mirror’s surface to redirect the light. These mirrors became an indispensable element of high-performance optical systems and have to meet extreme design and performance requirements such as high spatial resolution, smaller actuator pitch and high-density actuation arrays [18]. However, fulfilling these requirements leads to complicated systems with bulk electronics and huge installation footprints which become especially challenging, for example, with space-based instrumentation. The LUVOIR project [19] and the initial development of a hysteretic deformable mirror [20] have shown the demanding aspects in designing active elements for achieving stable wavefront correction over long periods of time (≈10 minutes) with picometer accuracy [21] for direct exoplanet search and observations. Therefore, lightweight, scalable and creative solutions are needed to open up new possibilities for the design of such devices and realize the high demands. Various actuator technologies are commonly used which include, for example, piezoelectric [22–24], electrostatic [25], thermal [26, 27], magneto-restrictive and shape memory alloy actuators [28] as well as voice coil/reductions actuators [18, 29]. New approaches can be implemented by metamaterials which are artificially designed materials with properties usually not occurring in nature [30, 31]. Considering mechanical metamaterials, whose main advantages here are scale-invariant mechanical behavior and reversible movements [32], some actuator technologies are based on lightweight, scalable and simple designs including kirigami cut patterns that lead to buckling-induced 3D deformations when stretched, and have the potential to be applied in adaptive optical systems. Examples are programmable hierarchical kirigami [33], and kirigami metamaterials with controllable local tilting orientations [34], hybrid cut patterns [35], or multidimensional deformations [36]. Studies that focused on developing controllable actuators by tuning and analysing cut patterns can

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be found in the literature [37, 38].

In this paper, we propose and numerically analyse kirigami cut patterns for coupling several lift-offs in a thin, scalable metasheet which enables us to design a modular actuation array that possesses a slim, in-plane design through a conversion of linear displacement into 3D motions. Its application is illustrated in detail by an example of a deformable mirror whose design and positioning of lift-offs are discussed. An algorithm is proposed for placing the cut patterns according to common adaptive optics methods such as Zernike polynomial fitting. The results are presented and the efficiency of the proposed metamaterial array is discussed, while practical guidelines are given.

II. MODULAR ACTUATION ARRAY BASED ON KIRIGAMI

Dias et al. [37] recently presented and experimentally evaluated a new concept of kirigami actuators whose dynamical pattern formation is controllable based on the arrangement of cuts introduced in a thin sheet. The cuts are functional cracks causing the system to buckle before failure through crack propagation. Therefore, due to a conversion of a linear displacement imposed on the boundary of a thin sheet, it is possible to generate predictable motions. One boundary of the sheet with introduced cuts was clamped while the opposite was subjected to a uniaxial extension perpendicular to the crack. This load condition causes the sheet to buckle in an energetically favorable mode corresponding to pre-designed shapes governed by the cuts. Four fundamental modes were elaborated and classified into roll, pitch, yaw and lift with the out-of-plane displacement occurring at the critical force [37].

Motivated by these results, we propose the design of multiple lift-offs in one kirigami sheet by means on a designed cut coupling for connecting two, three or more lift-offs in a symmetric arrangement, and numerically analyse them through finite-element nonlinear simulations. In the following, cut couplings for two, three or more lift-offs in one sheet are referred to as double, triple lift-offs or metasheets, respectively. The principles of this concept have been validated with the help of proof of concept experiments.

A. Design of cut patterns

To create a double and triple lift-off within one sheet, we need to introduce a separation forming convex polygons which can be done with two lateral cuts in the middle of the lift-offs. The lateral cuts redirect the tension so that the centers can lift up. A drop of the outer edges at the mid-line can occur while increasing the extension, but only showing small side effects with smaller out-of-plane displacement. Figure 1 visualizes the cut patterns of double and triple lift-offs. The sheets are clamped on the left side and extended on the right.

B. Numerical validation of cut patterns

The proposed cut couplings were validated numerically by means of finite-element simulations in Comsol Multiphysics 5.5 using the Structural Mechanics module with the shell interface. The kirigami sheets were modelled in 2D with a thickness of 0.127 mm, length of 182 mm and width of 100 mm. The material characteristics correspond to a Young’s Modulus of 3.5 GPa and Poisson’s ratio of 0.38. The lateral cuts have a length of 20 mm while the central cuts are 40 mm and placed in a distance of 8 mm. The lift-off area amounts to $18 \times 18 \text{ mm}^2$, and is at a distance (center to center) of 80 mm and 40 mm from the adjacent one for the double and triple lift-offs, respectively. One boundary was mechanically clamped while the other had an imposed displacement in regards to the average out-of-plane displacement of the lift-offs to trigger the buckling of the sheet. In addition, the surface included small, random imperfections (8 orders of magnitude smaller than the sheet thickness) modelled by a parametric surface for simulating the imperfection of the sheet flatness. Nonlinear displacement controlled stationary analyses were performed to examine the post-buckling behavior of the kirigami sheets.

Figure 2 shows the deformation of the lift-offs in isometric view and visualizes the out-of-plane displacement.
of the center points of the lift-offs plotted against the uniaxial tension in the metasheet. These results are characterized by a relatively small boundary extension of the kirigami sheet so that the drop of outer edges is comparatively low. It is possible to achieve higher lift-off displacements when the metasheet is optimized in its cut geometry. With increasing lateral cut lengths and concave unit cells, a rotation is initiated. At maximum tension, the lateral cuts take an upright position by flipping during the actuation process. This case is also demonstrated in Figure 2 (c).

The same principles hold for a further extension as long as the arrangement is symmetric. An example of a metasheet with several lift-offs that can be actuated simultaneously is given in Figure 3.

Based on these results, it is possible to design modular in-plane actuation arrays when single sheets are arranged in parallel and driven distributively by linear motors. This will allow an individual actuation of certain lift-offs and impose the required components in-plane. Due to the fact that sheets with different numbers of lift-offs have the same geometrical dimensions, large-scale arrays can be created and adapted to the desired needs. An example of an application in the field of adaptive optics is presented in Section III.

C. Proof of concept experiments

To validate the feasibility of the cut coupling and show that the behavior of the kirigami actuators is insensitive to scale or material, we performed proof of concept experiments. Test samples were manufactured from PVC sheets with a thickness of 0.3 mm using a VEVOR CNC 3018 engraver machine with a 5500 mW laser. The cut geometries were scaled down with a factor of 3.5 to obtain kirigami sheets with a total width of 28 mm and length of 60 mm. The proportions have been slightly adjusted to adapt the samples according to the test setup.

The experiments were carried out with an Instron 5944 Universal testing machine with customized clamps for thin sheets. Extension controlled tests were performed at a rate of 0.25 mm/min to a maximum extension of 1.8 mm. We tested three samples each for the different cut patterns (double and triple lift-off), and recorded their deformation with a Panasonic HDC-SD60 Full HD camera. The samples experienced light inelastic strains, but the actuation was reversible. Figure 4 presents the sheets in an isometric view at the maximum extension while Figure 5 shows the displacements during the experiments from a side view.
III. APPLICATION OF KIRIGAMI ARRAY IN ADAPTIVE OPTICS

We present a novel concept for deformable mirrors using the proposed modular kirigami actuation array. The structure is limited to a series of single metasheets mounted in parallel and subjected to a displacement by use of separate linear actuators. Each metasheet contains different cut patterns that couple vertical lift-offs that are purposely designed to create common deformations for light wave-front aberrations as illustrated in Figure 6. The parallel-arranged metasheets are designed in width and length such that they can cover the active area of the mirror. Beyond a sheet length-to-width ratio of about $L/w \approx 1$, the sheet length does not contribute to the crack deformation [37]. This allows us to flexibly adjust the length of the metasheets for the mounting of the linear actuators. In addition, kirigami actuators are weakly dependent on sheet thickness according to the present analytical model so that also the sheet thickness can be considered as a design parameter. The facesheet of the mirror is placed at a sufficient distance to the metasheets which can be determined by analysing lift-off displacements and desired membrane deformation. When the linear motors are actuated, the respective sheet will buckle and change its shape deformation to the encrypted lift-offs that generate a pressure on the mirror facesheet. Because it is not possible to create negative deformations on the membrane, all corrections are normalized to positive. We use the large span of operation of the kirigami actuators to generate the leveling between the actuators above zero. A specific selection of membrane material can also contribute with its stiffness to the mechanical coupling and smoothing between the actuators in the array. This mirror can be designed at the nano-, micro- or macroscales due to the scale-invariant mechanical behavior of kirigami sheets.

A. Algorithm for determination of best lift-off positions

The performance of deformable mirrors is evaluated by determining how well the actuators can reproduce a desired surface shape on the reflective membrane. Zernike polynomials are the preferred representation for light wavefront aberrations in adaptive optical systems [39] and are commonly chosen to test the possibilities of the actuator arrays. They are defined on a unit circle as functions of azimuthal frequency $p$ and radial degrees $q$, where $p \leq q$ using polar coordinates $(r, \theta)$. The set of polynomials can be given by

$$Z_p^q(r, \theta) = R_p^q(r) \cos(p\theta) \quad \text{for} \quad p \geq 0$$

$$Z_{-p}^q(r, \theta) = R_p^q(r) \sin(p\theta) \quad \text{for} \quad p < 0$$

(1)
where
\[
R_q^p(r) = \frac{(q-p)/2}{S^2((q+p)/2)!((q-p)/2-S)!} \cdot \] (2)

The deformed mirror shape in response to the actuation of a single actuator can be calculated by means of plate models and actuator influence functions. In the following, we propose an algorithm for placing the cut patterns according to selected low-order Zernike polynomials. Based on the influence functions [40], we can identify the optimal positions for every lift-off per sheet by extending it to a reverse method with initial pressure input and no dependency on any input position.

The optimization is done in two steps by means of minimizing the sum of the squares of the residuals made in the results of every single equation. In the first step, we consider the matrix equation from [40] given by
\[
z = MP
\] (3)

where \(z\) denotes the \(n \times 1\) vector containing the deflection per surface points, \(M\) the \(n \times m\) coefficient matrix, and \(P\) the \(m \times 1\) pressure vector. We note that the unknown in this case is the coefficient matrix which denotes the
influence functions per surface point. To perform a least-
square fitting on the matrix $M$ to identify the optimal
position based on the coefficient calculation, we vectorize
the matrix $M$ by stacking the columns of the matrix on
top of each other. The vectorized form of $M$ is denoted
by $V^{nm}(M)$ and given by

$$V^{nm}(M) := [a_{11}a_{21} \ldots a_{n1}a_{12}a_{22} \ldots
a_{n2} \ldots a_{1m}a_{2m} \ldots a_{nm}]^T. \quad (4)$$

The corresponding coordinates associated to each ele-
ment in $V^{nm}(M)$ are given by

$$\varepsilon_{n \times m} = (E_{11}, E_{21}, \ldots, E_{n1}, E_{12}, E_{22}, \ldots,
E_{n2}, \ldots, E_{1m}, E_{2m}, \ldots, E_{nm}). \quad (5)$$

The pressure vector must be $n$-times repeated and trans-
posed, and can be denoted as $P^T$. For compactness, the
vector $V^{nm}(M)$ is denoted as $\text{vec}(M)$ in the following.
Using the Kronecker product, matrix multiplication can be
expressed as a linear transformation of vectorized ma-
trices. Hence, the first least-square problem is associated
with

$$\text{vec}(z) = (P^T \otimes I) \text{vec}(M) \quad (6)$$

which can be solved by standard numerical techniques.
The system is underdetermined with an infinite num-
ber of solutions. We find the smallest solution by min-
imizing $\text{vec}(M)$ subjected to the constraint $\text{vec}(z) =
(P^T \otimes I) \text{vec}(M)$ and solve according to

$$\text{vec}(M) = K^T(KK^T)^{-1}z. \quad (7)$$

After the solution $\text{vec}(M)$ is obtained, the vector can be
transferred back to the initial coefficient matrix $M_{ij}$
which denotes the influence function at surface positions
labeled $i = 1, \ldots, N_a$ per $j$-th actuator.

In the second step, we calculate optimal positions of
the lift-off based on the obtained coefficients. For this,
the formulation of Case V from [40] is rewritten and the
radial limits substituted by the center point of the
approximate lift-off positions to obtain a nonlinear mul-
tivariable function. This function can be given by

$$f(x) = M_{ij} + \left(\frac{1}{2\pi} \Delta \phi_j[-\ln r_i][r_i^2 - (x - \frac{p_w}{2})^2] / 2
- \sum_{n=1}^{\infty} \frac{n^2}{n^2(n + 2)} r_i^{2n - 1} \times \left[ \left( \frac{r_i}{x} \right)^{n + 2} - \left( \frac{r_i}{x - \frac{p_w}{2}} \right)^{n + 2} \right] \times [\sin n(\phi_{2j} - \phi_i) - \sin n(\phi_{1j} - \phi_i)]
+ \frac{1}{2\pi} \Delta \phi_j \left[ (x + \frac{p_w}{2})^2 \left( \frac{1}{2} - \ln \left( x + \frac{p_w}{2} \right) \right) - r_i^2 \left( \frac{1}{2} - \ln r_i \right) \right] / 2
- \sum_{n=1}^{\infty} \frac{1}{n^2} r_i^n \left( (x + \frac{p_w}{2})^{n + 2} - r_i^{n + 2} \right) / (n + 2) + \alpha \times [\sin n(\phi_{2j} - \phi_i) - \sin n(\phi_{1j} - \phi_i)] \right) \right) \quad (8)$$

where $\Delta \phi_j$ is the approximated lift-off size in the angu-
lar coordinate calculated by the subtraction of upper by
lower angular limit $\phi_{2j}$ and $\phi_{1j}$; $r_i$ is the radial posi-
tion on a specified surface point $i$; $x$ is the center position of
the lift-offs; $p_w$ is the lift-offs’ width, and $\alpha$ is an addi-
tional factor based on the radial limits. The infinite sums
are approximated by using a lower limit on series term
size (before multiplication by sine term) of $1 \times 10^{-7}$.

To enable finding the optimal position for the lift-offs
over the length of a single kirigami actuator sheet, we
make a preselection of actuator positions relevant to the
corresponding Zernike polynomials. For that, we rely
on an important property of the Zernike polynomials,
namely, the rotational symmetry that allows the poly-
nomials to be expressed as products of radial terms and
functions of angle, $r(\rho)g(\theta')$. Here $g(\theta')$ is con-
tinuous and repeats itself every $2\pi$ radians. Based on these
symmetries, we will determine a certain amount of lift-offs in
one sheet (for simplicity, two) for a specific Zernike poly-
nominal from the basis functions presented in Figure 7.

The preselection of positions is intuition-based and fol-

The nonlinear least-squares solver (lsqnonlin) of Mat-
lab [41] starts at the point \( x_0 \), which is defined in the most likelihood area based on apriori knowledge, and finds a minimum of the sum of squares of the defined vector-valued function defined as

\[
f(x) = \begin{bmatrix} f_1(x) \\ f_2(x) \\ \vdots \\ f_n(x) \end{bmatrix}.
\] (10)

### B. Arrangement of lift-offs

To illustrate the results, we have run several Matlab (Matlab R2019a) simulations to evaluate the best positions for the lift-offs. Within the concept of a deformable mirror, we actuated 11 kirigami actuators with two lift-offs each. Only the outer sheets have a triple lift-off to cover the open edges. The mirror diameter (active area) was normalized to a radius of 1 while the initial dimensions amount to an active area of 50 mm, a membrane diameter of 70 mm, a sheet width of 4.5 mm and a lift-off size of \(1 \times 1 \text{ mm}^2\) with a rather trapezoidal shape due to the plate model. The membrane surface tension was set to 15 N/m.

The horizontal distance was restricted to the centerlines of every sheet which correspond to 10/11, 8/11, 6/11, 4/11, 2/11, 0, -2/11, -4/11, -6/11, -8/11, and -10/11 considering the arrangement in terms of the unit disc from right to left numbering the sheets from 1 to 11 in ascending order. The surface points were distributed in a squared arrangement to fully cover an area that contains the unit disc. In total, 100 surface points have been selected at a horizontal distance of 0.01 per unit disc radius.

The preselection was done by choosing certain kirigami actuators to be responsible for reproducing specific basis functions as summarized in Table I. The initial distribution at \( x_0 \) is listed in Table II. The results for the optimized lift-off positions are illustrated in Figure 8 and further specified in Table II.

### TABLE I: Summary of activated sheets with 11 kirigami actuators in the deformable mirror per selected basis function of the Zernike polynomials (ZP). A sheet is activated when the pressure (P) is set, otherwise it is zero.

<table>
<thead>
<tr>
<th>Kirigami metasheet</th>
<th>ZP #1</th>
<th>#2</th>
<th>#3</th>
<th>#4</th>
<th>#5</th>
<th>#6</th>
<th>#7</th>
<th>#8</th>
<th>#9</th>
<th>#10</th>
<th>#11</th>
</tr>
</thead>
<tbody>
<tr>
<td>w_1</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>0</td>
<td>0</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
</tr>
<tr>
<td>w_2</td>
<td>P</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>P</td>
</tr>
<tr>
<td>w_3</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
</tr>
<tr>
<td>w_4</td>
<td>P</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>P</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>P</td>
</tr>
<tr>
<td>w_5</td>
<td>P</td>
<td>0</td>
<td>0</td>
<td>P</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>P</td>
<td>0</td>
<td>0</td>
<td>P</td>
</tr>
<tr>
<td>w_6</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
</tr>
<tr>
<td>w_7</td>
<td>P</td>
<td>0</td>
<td>0</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>0</td>
<td>P</td>
<td>0</td>
<td>0</td>
<td>P</td>
</tr>
<tr>
<td>w_8</td>
<td>P</td>
<td>P</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>P</td>
<td>0</td>
<td>P</td>
<td>P</td>
<td>P</td>
</tr>
<tr>
<td>w_9</td>
<td>P</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>P</td>
<td>0</td>
<td>0</td>
<td>P</td>
<td></td>
</tr>
<tr>
<td>w_10</td>
<td>P</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>P</td>
<td></td>
</tr>
</tbody>
</table>

Figure 9 presents the active area of the membrane when all lift-offs are activated with a pressure set to 1 N/m for simplicity. The membrane displacement was calculated based on the presented model in [40]. In addition, Figure 10 shows the basis function \( w_2 \) and \( w_5 \) to illustrate the principle of fitting the mirror surface.
TABLE II: Summary of the results for a deformable mirror actuated by 11 kirigami actuators with two or three lift-offs each. The optimal positions of every lift-off in regards to the selected Zernike polynomial (ZP) are given in the column of \( x \), and are considered as symmetric arrangement on the kirigami sheet.

<table>
<thead>
<tr>
<th>Sheet</th>
<th>Height centerline</th>
<th>ZP</th>
<th>( x_0 )</th>
<th>( x )</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>10/11</td>
<td>( w_5 )</td>
<td>0</td>
<td>0.4100</td>
<td>1</td>
</tr>
<tr>
<td>#2</td>
<td>8/11</td>
<td>( w_9 )</td>
<td>0.45</td>
<td>0.6800</td>
<td>2</td>
</tr>
<tr>
<td>#3</td>
<td>6/11</td>
<td>( w_8 )</td>
<td>0.35</td>
<td>0.7984</td>
<td>2</td>
</tr>
<tr>
<td>#4</td>
<td>4/11</td>
<td>( w_7 )</td>
<td>0.7</td>
<td>0.9300</td>
<td>2</td>
</tr>
<tr>
<td>#5</td>
<td>2/11</td>
<td>( w_3 )</td>
<td>0.15</td>
<td>0.2050</td>
<td>2</td>
</tr>
<tr>
<td>#6</td>
<td>0</td>
<td>( w_2 )</td>
<td>0.85</td>
<td>0.2228</td>
<td>2</td>
</tr>
<tr>
<td>#7</td>
<td>2/11</td>
<td>( w_3 )</td>
<td>0.15</td>
<td>0.2050</td>
<td>2</td>
</tr>
<tr>
<td>#8</td>
<td>4/11</td>
<td>( w_7 )</td>
<td>0.6</td>
<td>0.9300</td>
<td>2</td>
</tr>
<tr>
<td>#9</td>
<td>6/11</td>
<td>( w_8 )</td>
<td>0.35</td>
<td>0.7984</td>
<td>2</td>
</tr>
<tr>
<td>#10</td>
<td>8/11</td>
<td>( w_9 )</td>
<td>0.45</td>
<td>0.6800</td>
<td>2</td>
</tr>
<tr>
<td>#11</td>
<td>10/11</td>
<td>( w_5 )</td>
<td>0</td>
<td>0.4100</td>
<td>1</td>
</tr>
</tbody>
</table>

FIG. 9: Surface plot of the mirror membrane (active area) when all lift-offs are activated and exert the same pressure. The vertical colorbar gives the membrane displacement in [m].

IV. DISCUSSION AND CONCLUSIONS

In summary, we have designed and applied new concepts of cut coupling in kirigami actuators and numerically analysed their out-of-plane displacements by finite-element simulations. Proof of concept experiments demonstrated the feasibility of the principles and have shown that the behavior of kirigami actuators is insensitive to scale and material. The lift-off positions in the mechanical metasheets can act as actuators when they are evoked by a linear displacement of the metasheet itself. Based on a parallel arrangement of several kirigami sheets with either double, triple or multiple lift-offs, modular actuation arrays are generated which can be applied, for example, in adaptive optics. A new concept for a deformable mirror was illustrated in detail and optimized positions for the lift-offs of the actuation array were determined by means of a developed reverse position algorithm. Due to the small number of lift-offs in the example, high surface fitting accuracy could not be reached. Nevertheless, the number of actuators and thus, the degrees of freedom, can be increased by exploring larger arrays. For example, high-precision performance requires dense actuator arrays. The current state of the art is 64 × 64 actuators demonstrated by fully functional deformable mirrors of Boston Micromachines Corporation (correction in astronomical imaging instruments) [42] and AOA Xinetics (correction of high-energy and high average power lasers) [43]. To achieve modular arrays with a few thousand lift-off positions, more com-
plex metasheets have to be designed and aligned in such a way that the covering of the active area of the mirror is maximized. It may be advisable to break up the parallel arrangement and position the individual sheets in an optimized way. Due to the large deformations that can be achieved by the lift-off mechanism with optimized cut geometry, the sheets no longer have to be leveled in-plane but in their peak deformation instead, and could also generate asymmetrical patterns when positioned with over-lay. However, for the correction of low order aberrations and other sorts of applications fewer numbers of actuators could be also appropriate.

The proposed system is characterized by a scalable design ranging from nanoscale to macroscale since the kirigami actuators have a scale-invariant mechanical behavior. Therefore, it has a promising potential for various applications in the field of adaptive optics. The developed modular array presents a lightweight solution since the actuators can be made, in the simplest sense, of paper like traditional kirigami. Nevertheless, additional linear actuators are required to activate individual sheets in a targeted manner. Here, the number of lift-offs chosen must be compared to the number of required linear actuators. Then it can be reflected whether this concept is advantageous for the application-related demands.

Moreover, kirigami structures show relative independence from their base material which significantly expands the choice of material. By optimizing the cut geometries for different materials, comparable movements can be achieved within the actuation. In addition, the overall arrangement comprises an in-plane design due to the fact that linear displacements are converted to an out-of-plane deformation which opens up the possibilities for compact and slim layouts for optical systems such as the deformable mirror in space-based applications.

The presented analysis needs to be exploited by investigating and measuring the generated pressure of the lift-offs when the kirigami sheet is operated. This will determine which deformation profiles can be achieved for different membranes and materials. It is also necessary to determine a required distance between an actuation array and a membrane so that the buckling-induced lift-off will always take its favorable state and function in a reliable way.

While we have only discussed symmetrical arrangements in the positioning of lift-offs within one sheet and the placement of metasheets for covering the active area of the mirror, asymmetrical cut patterns and arrangements should be explored, which would increase the complexity and lead to more flexibility in designing the modular array. This could eliminate the limiting factor related to the response accuracy for a dynamic input and degrees of freedom.

The pre-programmed behavior of the individual actuators must be well thought out for the application. By means of suitable combinations of encrypted lift-offs, the possibilities can be extended such that a good number of correction elements and lift-offs can be connected to each other. The generation of a tailored control strategy of the mirror linked to the wavefront sensor and computing system is advisable. While the presented concept of actuating the deformable mirror with a modular array contains only one layer of information, in the future it may be possible to encode several layers into one metasheet and then evoke the desired combination of lift-offs in a targeted manner. Research works such as [33, 38, 44] show how different layers of information can be textured.

The kirigami sheets can be further optimized and adapted to other specific applications. Based on the proposed idea, this could include, for example, the (static) correction of small misalignments, aberrations, imperfections or undesired surface textures in other materials. For that, different cut couplings might be important and instead of pure symmetrical arrangements, other fundamental modes of roll, pitch or yaw and their combination could be explored.

In conclusion, the modular kirigami array for distributed actuation systems is characterized by its reliability and robustness since this concept would not suffer from a total failure when a single sheet loses functionality. The array can be upgraded and improved by replacing and changing the corresponding metasheets. The assignment of single functions to individual sheets offers high flexibility in the design. However, this concept is affected by the losses and suboptimal use of space due to the transitions between single kirigami actuators with simple cut coupling and small number of lift-offs. For that reason, the investigation of more complex cut couplings is important to advance this actuation system for applications in adaptive optics.

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