

Adaptive Fluid Lens and Sunlight Redirection System

Exploring a novel way of redirecting and altering sunlight in large span roofs

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Abstract. *The paper describes a novel system to alter and redirect sunlight under large span roofs with the help of a fluid lens system. Focus lies on the computational design, testing, measurement and evaluation of the performance of a physical prototype.*

Keywords. *Daylight; large span roofs; optics.*

OBJECTIVE

The general aim of the presented research is to develop a design methodology with the help of computational tools and prototypes in order to be able to design adaptive daylight systems in large span roofs under consideration of user and functional requirements and respectively daylight performance aspects. Adaptive solutions for vertical facades with relatively small rooms and individual requirements of the inhabitants in form of e.g. louvers are well researched and applied. In the case of large span roofs where the horizontal part of the envelope exceeds the vertical one for admitting light, the design requirements and parameters for daylighting are different. Here collective lighting requirements and adjustability for a higher amount of inhabitants, diversity of functions, larger spatial entities and the geometrical relations between sun path and general roof alignment towards the zenith play a major role. However not only quantities of light according to regulations or qualitative aspects in form of visual

comfort but also energetic aspects in terms of heat gains are part of the design and research scope. The research on the adaptive fluid lens and sunlight redirection system described here is one of the case studies being developed within the framework of an ongoing PhD research at TU Eindhoven. In this specific case the objective is to find a way to capture and utilize sunlight to be used under a large span, horizontal roof in order to be adaptively redirected where needed and dynamically treated or altered in such a way that it can fulfill various functional aspects (Figure 1). This horizontal “window” has to continuously mediate between the dynamic yet known path of sunlight in relation to the location and the possible change of interior use or functionality and thus lighting requirements.

PRINCIPLE

The adaptive lens and sunlight redirection system consists of two major components (Figure 2). Firstly

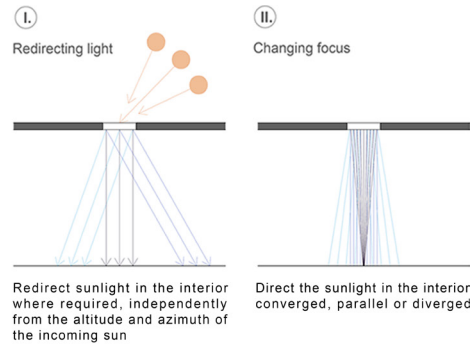
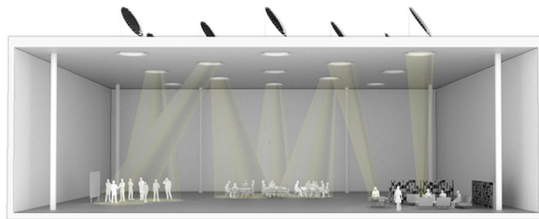


Figure 1
Objective of the adaptive fluid
lens and sunlight redirection
system.

Objective

a set of mirrors which as a whole orient themselves towards the general horizontal sun direction (azimuth) and individual rows of mirrors which are rotated in the same angle according to the sun altitude. The altitude orientation is done in such a way that the incoming sunrays are reflected downwards into an aperture which houses the adaptive lens. The lens itself consists of a transparent horizontal lower surface, a casing and on top an elastic deformable and transparent membrane. By changing the internal volume via pumping a clear and transparent liquid, the shape of the membrane can be changed from concave to convex and continuously all the stages in between, thus being able to diverge or converge direct light according to Index of Refraction (Taylor, 2000) and Snell's law (Taylor, 2000).

DESIGN APPROACH

The design approach consists of five steps. (1) Physical principles (2) Associative 2-D and 3-D models (3) Simulation (4) Prototype (5) Prototype measurements and evaluation

Step 1: Physical principles

In order to apply physical principles like Snell's law of Refraction or Fresnel's equation for reflection and transmission (Bennett, 1995) several associative files were set up in the Rhino/Grasshopper environment in order to see the effects of light refraction, transmittance, absorption or reflectance of various geometry/material combinations and evaluate the possibilities for sunlight redirection and alteration.

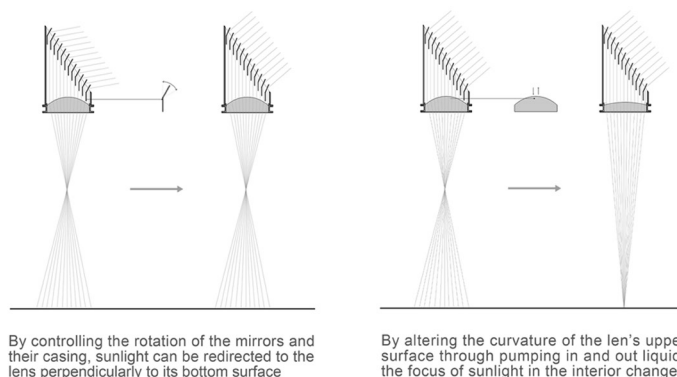
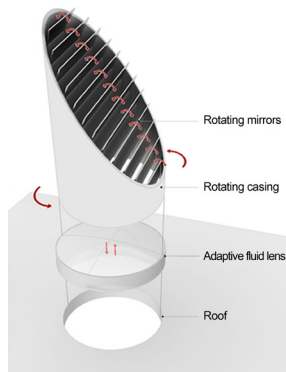


Figure 2
Description of the proposed
system.

Table 1
Sun altitude occurrences for Munich.

Percentage of the day that the altitude of the incident sunlight is at a specific angle range														
2013	Munich	PERCENTAGE												TOTAL (%)
	Date	21-Jan	21-Feb	21-Mar	21-Apr	21-May	21-Jun	21-Jul	21-Aug	21-Sep	21-Oct	21-Nov	21-Dec	Jan-Dec
	DST	off	off		on	on	on	on	on	on	on	off	off	
	< 0°	62,50	56,25	50,00	41,67	35,42	34,38	36,46	42,71	50,00	56,25	63,54	65,63	49,57
	0°-10°	11,46	9,38	8,33	9,38	10,42	8,33	9,38	8,33	8,33	9,38	10,42	12,50	9,64
	10°-20°	15,63	10,42	8,33	8,33	8,33	10,42	8,33	8,33	8,33	10,42	16,67	21,88	11,28
	20°-30°	10,42	15,63	10,42	8,33	8,33	8,33	8,33	8,33	10,42	16,67	9,38	0,00	9,55
	30°-40°	0,00	8,33	12,50	9,38	8,33	8,33	8,33	9,38	12,50	7,29	0,00	0,00	7,03
	40°-50°	0,00	0,00	10,42	11,46	9,38	8,33	9,38	11,46	10,42	0,00	0,00	0,00	5,90
	50°-60°	0,00	0,00	0,00	11,46	12,50	10,42	11,46	11,46	0,00	0,00	0,00	0,00	4,77
	60°-70°	0,00	0,00	0,00	0,00	7,29	11,46	8,33	0,00	0,00	0,00	0,00	0,00	2,26

Data collected from: Solar elevation angle (for a day) calculator, <http://keisan.casio.com/exec/system/1224682277>

Hours of sunshine per day

Munich	HOURS OF SUNSHINE											
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
h. per day	1,97	3,00	4,13	5,23	6,42	6,97	7,65	6,87	5,77	4,16	2,30	1,58

Data collected from: Climatedata eu, <http://www.climatedata.eu/climate.php?loc=gmx0087&lang=en>

Step 2: Associative 2-D and 3-D models

Snell's laws is most relevant and was translated into associative 2-D sectional drawings of a light converging/diverging lens and a mirror system in order to understand the capabilities and performance of the proposal under changing light directions. In this initial step an adaptive lens system was set up which is able to change the radius of an upper lens and Index of Refraction of the contained liquid according to material properties of existing fluids and Snell's law in order to focus or diffuse light. Here an array of vectors is refracted within the lens and made visible via a bundle of lines to serve as design and early evaluation tool. The change in altitude angles of the sun leads to a change of the focal point of the refracted light and it showed that the redirection possibilities of a lens are limited. This means in order to keep the light e.g. diverged in terms of a constant area size, the membrane's geometry has to be continuously changed by pumping liquid due to the resulting change of the focal point in relation to the sun's changing altitude. For this fact and the lens' limited possibility of light redirection into the interior a secondary system for light redirection is required. Therefore several options like trapping light by internal reflections (glass fiber principle), a rotatable prism system or plain mirrors were evaluated. The system of rotating mirrors was favored, because this proofed to be more "straightforward" and promising in terms of light redirection under a greater va-

riety of altitude angles. To reduce the height of the mirror system located on top of the lens, an array of mirrors was chosen instead of one larger mirror. This approach poses several challenges in term of overshadowing each other and being able to redirect sunlight in different quantities according to the sun's altitude angle and it turned out that there is no universal system which works equally well in for every sun altitude. Therefore it is necessary to take a closer look at several design parameters and become specific about location, the respective available hours with sunshine, the annual and daily sun path and the prevalence of certain ranges of sun altitude angles and times of occupancy of the building. By matching these parameters it is possible to narrow down the target range of altitude angles where the redirection of sunlight is working a hundred percent. By choosing a design example in Munich and as function a train station which is heavily frequented during the rush hours, lower sun altitude angle ranges, which occur more frequently during mornings and evenings but also during spring, autumn and winter become more relevant (Table 1). By applying the Galapagos genetic algorithm solver [1] to generate and validate variations of the fixed inclination of the whole mirror array, the distance, sizes and amounts of the individual mirrors, a whole set of design solutions is produced which redirects sunlight altitudes perpendicularly to the ground by a 100% within a Δ range of 30° (Figure 3). It is then a

Panel's rotation: 55°, No. of mirrors: 13, Mirrors' width: 0,20m

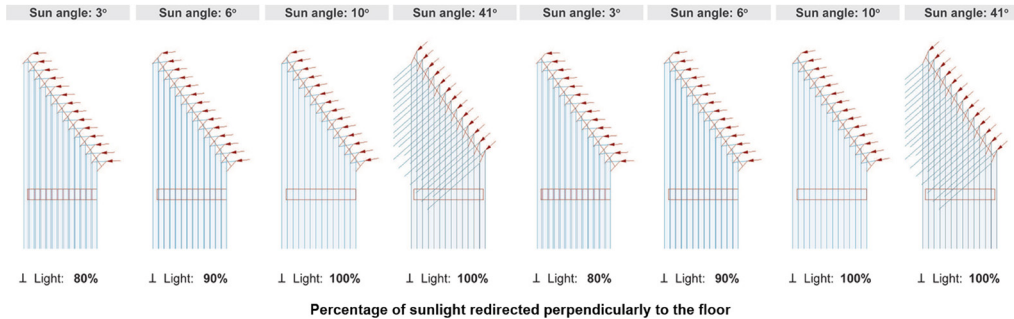


Figure 3

Grasshopper study on the percentage of sunlight redirected perpendicularly to the floor according to the sun altitude.

matter of selecting the configuration which is most suitable for the design task at hand. In the example of Munich, a mirror configuration was eventually chosen which operates perfectly between 10-40 degrees. After evaluating the design principles in the earlier steps associative three-dimensional files were set up to further evaluate the behavior of the lens and mirror system and also to have a geometrical input for later daylight simulation.

Step 3: Simulation

The simulations were done via Diva/Radiance [2] and the V-Ray renderer [3] also available for Rhino 3D. The Radiance simulation was initially regarded as being important because it is able to show physical values like illumination in lux or luminance in cd/m². This would enable to check the performance for actual conditions and requirements as stated in e.g. building codes. However the various simulations done proved to be not accurate since Radiance for windows is not able to calculate optical effects with dielectric material properties properly (Jacobs, 2012). This has to be done in the Linux environment with the help of a photon mapping module, which was developed by the Fraunhofer ISE [4]. This approach for simulating several different and adaptive geometries and the consequence to manually input the data in Radiance for Linux defies the seamless integration of parametric modelling and simulation. Curiously contemporary render engines such

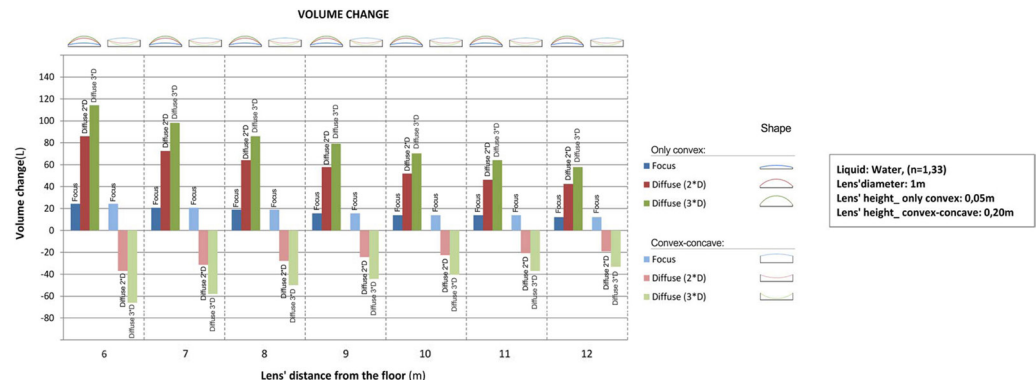
as V-Ray are able to calculate caustic effects [3] with physically correct material properties and Index of Refraction but are not able to display physical values such as Illuminance, etc. It was therefore decided to design and manufacture physical prototypes for the performance evaluation in accordance with the earlier findings from the associative 2-D and 3-D models.

Step 4: Prototype

During the design process for the prototype, research was done for lens diameters, change of volume and weight on the roof for a 1:1 case (Figure 4). In general it can be said that the higher a roof is situated above ground the less of a shape change in the lens has to occur in order to achieve a desired effect. By studying these parameters it was decided that a lens with a diameter of 1m would be optimal for many applications in terms of weight and required volume change within the lens.

The final prototypes which serve as proof of concept and are used for daylight performance measurements were manufactured in the scale 1:10 (Figure 5). The majority of parts including the mechanical parts like gears and cograil for the sunlight redirection device are made of white ABS plastic and 3-D printed by a Fused Deposition Modeling (FDM) printer. For the mirrors 3M™ Solar Mirror Film 1100 is applied on the rotatable ABS fins. The membrane for the lens is a self-cast and baked Polydimethylsilox-

Figure 4
Volume change required for the convergence and divergence of light in relation to the room height.



ane (PDMS) membrane provided by Michael Debije at Functional Devices research group of the Department of Chemical Engineering and Chemistry at TU Eindhoven. Water with an Index of Refraction of 1,33 (Lide, 2009) is used as optical liquid. Other liquids like colorless and transparent oils which generally have a higher Index of Refraction are also thinkable.

Step 5: Prototype measurements and evaluation

The physical experimentations with the 1:10 scale prototype aimed at testing the performance of the system under clear sky with sun (Test 1-3) and cloudy sky conditions (Test 4) (Figure 6). For the simulation of the clear sunny sky, a Solar Simulator was used, providing directional light, while for the over-

cast sky, an Artificial Sky Simulator was employed, to achieve diffuse lighting conditions. Through all test series, illumination measurements were done using a Hagner Digital Luxmeter EC1 and lamination pictures were taken with a Canon EOS 60 D and further processed in Photolux 3.2. [5]

Clear sky with sun, Test 1 and 2 set up

The first two series of tests (Test 1 and 2) focused on the performance of the adaptive fluid lens alone under clear sky, supposing an ideal situation of 100% incoming perpendicular to the floor light, which would occur if the sun redirection systems functioned perfectly. To simulate the above, the altitude of the solar simulator was set to a 90° angle. Two different in size closed boxes (Test 1: 0,5*0,5*0,35m,

Figure 5
Aspects of the adaptive fluid lens and sunlight redirecting system prototype in 1:10 scale.

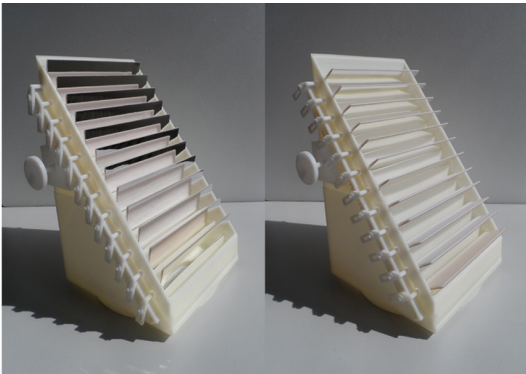




Figure 6
Test settings: From left: Solar Simulator at a 90° altitude (Test 1), Solar Simulator inclined at a 30° altitude (Test 3). Artificial Sky Simulator (Test 4).

Test 2: 0,7*0,7*1m) with a circular opening at the center of their top surface for the 10cm diameter fluid lens to be placed over, were used as room models. Water was pumped in and out of the two syringes connected to the lens, to reconfigure its shape from neutral to convex and concave. These tests approximate the performance of a 1m diameter fluid lens in a 3,5m and 10m high room respectively.

Test 1 and 2 observations and comparison

The tests showed that under clear sunny sky conditions the light is indeed diverged or converged according to the configuration of the membrane and similarly to the predictions from the grasshopper models (Figure 7). Comparing the two room scenarios and scaling up the results to 1:1, it is confirmed

that a lens of 1m diameter is more efficient over a 10m high room than a 3,5m room, as previously estimated. To be more specific, in the case of the 1m box, the removal of 55ml of water from the lens in neutral state causes a circular lit area on the floor of 0,46m diameter (concave lens) while the addition of 12ml produce a focal point on the floor of 0,01m diameter (convex lens) (Figure 8). In full scale the values would be 10m, 55L, 4,6m, 12L 0,1m. At the 0,35m high box r, when an almost equal water volume (58ml) is removed from the neutral lens, a lit area of 0,22m is produced. Furthermore, in order to achieve focused light on the floor at a point of 0,005m diameter, 26ml of water need to be added to the neutral lens. In full scale the values become 3,5m, 58L, 2,2m, 26L and 0,05m accordingly. In general, at the con-

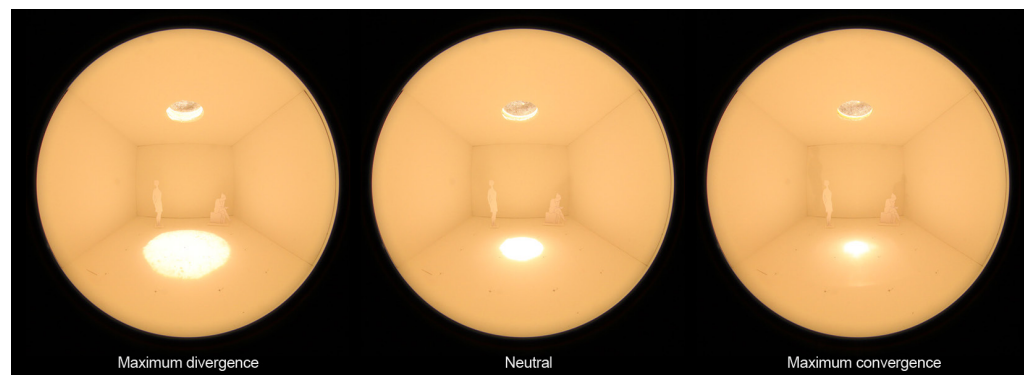
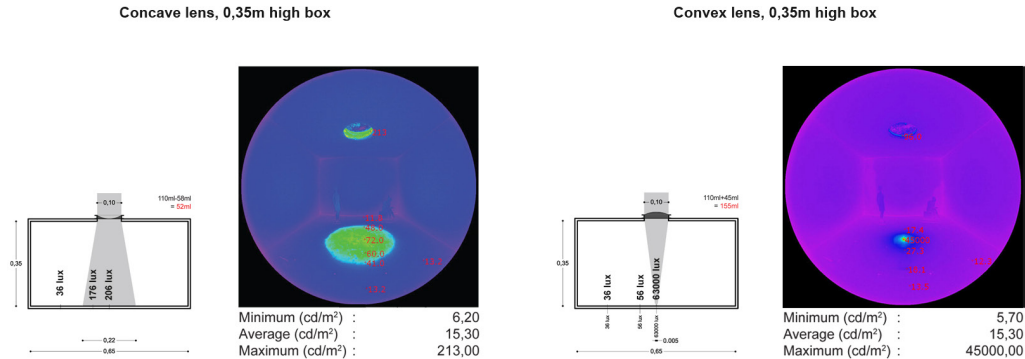


Figure 7
Differences in the quality of shadows from the concave to the convex mode of the adaptive fluid lens.

Figure 8
Test 1: comparison between
the diverged and converged
mode.



cave mode, the lens is acting as a spotlight spreading out the received sunrays. The light hitting the floor surface and reflected by it causes the formation of soft shadows by the scaled human figures placed at the periphery inside the box.

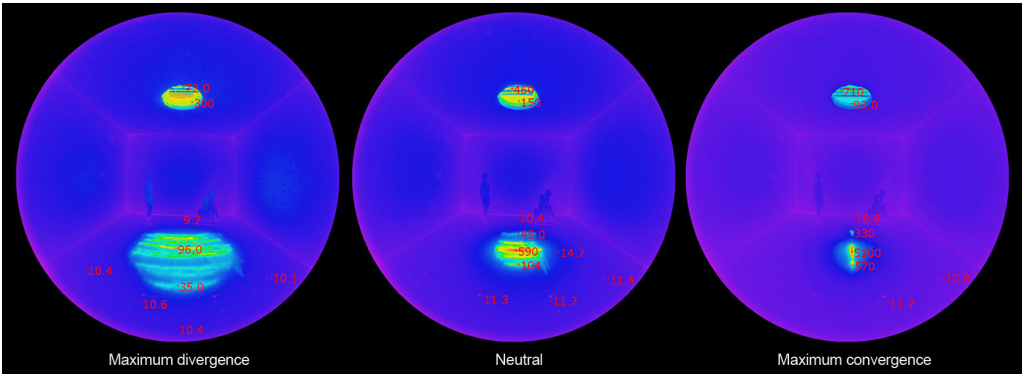
Considering the focused mode, the flux density at the center of the floor surface (63.000lux for Test 1 settings) is excessively high in comparison to the density measured at the periphery (36lux for Test 1 settings). Given the fact that in Test 1 the sun simulator produces a value of 908lux at the floor center and scaling up the findings, we can assume that on a clear sunny day in summer where 100.000lux reach the ground (Flesch, 2006), the flux density will be 6.940.000lux at the center and 4.000lux at the periphery. Such concentration of light is responsible

for high contrast ratios in the room that not only exceed the acceptable contrast thresholds for visual comfort but also surpass the 1:1000 ratio which is the range of brightness the human eye can perceive (Green et al, 2008). The most extreme converging mode might not be applicable for daylighting. However other uses are possible as described in the outlook section of this paper.

Test 3 set up

Test series no. 3 examine the effectiveness of the sunlight redirection system on a clear sunny day (Figure 9). For these tests, the 0,5*0,5*0,35m box was used as a room model and the solar simulator was set at 30° sun altitude, where the sunlight redirection system is expected to be 100% efficient accord-

Figure 9
Test 3: different lens configurations.



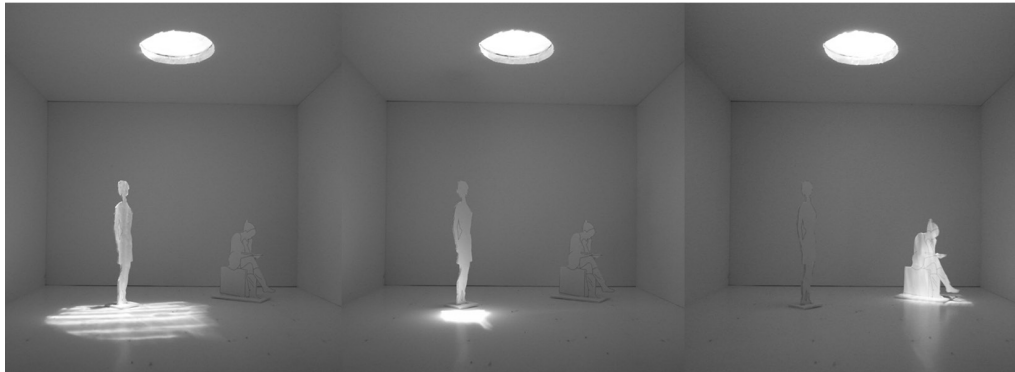


Figure 10
Adaptive daylight in the
interior.

ing to the Grasshopper/Galapagos models. The system was placed over the fluid lens at the top of the box and the mirrors were rotated as such, to direct the received light perpendicularly to the ground.

Test 1 and 3 observations and comparison

Although the sunlight redirection system manages to redirect the light perpendicularly to the ground, the system in combination with the lens do not succeed in bundling all the rays in one focal point but in fact a linear series of focal points is noticed. This deviation is caused by imperfections of the mechanical system controlling the rotation of the mirrors. It can be derived that even minor deviations of the mirrors from the correct inclination can direct the light in a non-desired direction as well as light scattering is further enhanced if the film is not evenly applied over the ABS lamellas. The imperfections at the rotation mechanism are also responsible for the presence of more accentuated shadows on the floor cast by the row of mirrors. Minor shadows are of course expected at the neutral and diverging modes of the lens due to the thickness of the mirrors but not to the observed extent.

Light redirecting possibilities

The prototype showed that initial expectations in terms of light redirection capabilities of the systems were by far exceeded (Figure 10). In the Test 3 configuration it was possible to redirect light within

the sun's azimuth alignment until reaching the wall. In the other direction it was possible to reach 90% of the space (0,5m*0,5m) with the spot. The Test 2 configuration in combination with the redirection device did not fit under the sun simulator. However it should be noted that, the higher the ceiling is located above ground, the more the range and performance is increased in terms of light redirection. Due to the height of the redirection device itself the area of illumination is more reduced the further the light beam is astray from the vertical redirection configuration. Furthermore it will also be interesting to see the interaction and lighting design possibilities of several devices together.

General findings regarding the fluid lens under clear sky conditions

The light and heat absorption by the water volume is another issue worth to be discussed as during clear sky conditions, the lux value on the floor surface under the opening is reduced in both Test series 1 and 2 by 31% when the lens at its neutral state is placed over the opening. The Beer-Lambert Law explains the logarithmic relationship between the transmission of light through a substance, the thickness of the medium and the wavelength of the light, proving that the intensity of light decreases exponentially with the increase of the water depth (Ryer, 1997). Taking into account that the light absorption coefficient of water for violet light (380nm wave-

length) is $0,00011\text{cm}^{-1}$ and for red light (725,5nm wavelength) is $0,01678\text{ cm}^{-1}$ (Pope et al, 1997) and by applying the Beer-Lambert law for a water depth of 1,4cm (water depth at the neutral state of the prototype), it can be concluded that 0,035% of violet light and 5,26% of red light will be absorbed by the water volume. Considering the full scale lens, the occurring light absorption will increase due to the 10 times higher water depth. Calculations show that 0,35% of violet light and 41,77% of red light will be absorbed by the water volume. Moreover, due to the selective color absorption property of water, the light exerting the lens will have a slight blue hue.

In addition, the light absorption coefficient of water for wavelengths of 1.000nm to 1.000.000nm ranges from $0,339\text{ cm}^{-1}$ to $128,2\text{ cm}^{-1}$ meaning that water is strongly absorbing infrared light (Zolotarev et al, 1969). Of the radiant energy emitted from the Sun, approximately 50% lies in the infrared region (Fu, 2003). This energy is to be perceived as thermal energy, absorption of the infrared light leads to the reduction of the amount of heat entering the room from the lens. Due to the high specific heat index of water, the lens is expected to act as a thermal mass that absorbs, stores and releases heat where the penetration of heat is delayed.

Cloudy sky

Test series no.4, conducted in the Artificial Sky Simulator, study the performance of the system in the worst case scenario, that of a cloudy winter day. For these tests the $0,5*0,5*0,35\text{m}$ box was used first with the fluid lens alone at its top opening (Test 4A) and then with the sunlight redirection system placed over (Test 4B). According to the findings, the incoming light is evenly distributed rather than diverged or converged.

When comparing Test 4A and 4B, we conclude that the sunlight redirection system is reducing the amount of incoming light by 47,8% at the area under the opening (flux density is reduced from 53lux to 28lux) and by 57,5% at the periphery of the space (from 46lux it becomes 19lux). To scale up the measurements to real overcast conditions, we consider

a typical flux density at ground level on a cloudy winter day of 4000lux (Flesch, 2006) and relate it to the 962lux measured outside next to the box. This results in 220lux at the center of the floor area and 191lux at the periphery when only the fluid lens is present, and in 116lux and 79lux respectively when the sunlight redirection system is added.

CONCLUSION

Assessment of the combined system

The physical experimentations prove the ability of the system to quickly adapt not only in order to converge/diverge the sunrays but also to redirect the incident light according to the needs of the interior space over almost the whole floor surface. The system successfully proved to be able to function as a daylight spotlight which can adaptively react to the moving sun position as well as interior lighting requirements. The changes between different modes occur gradually rather than abruptly and thus are not disturbing to the user.

It is however concerning the high contrast ratio observed in some of the tests and the probability of glare needs to be evaluated. Also the illumination of the interior when more than one adaptive sunlight redirecting modules are installed in proximity has to be determined. The performance under worst case, cloudy sky conditions appears to be sub optimal and this would either determine a certain amount of lenses required on the roof or would suggest an application at a location with a high amount of sunny hours. By applying the system at the more southern hemisphere location it would not only be more effective in terms of direct sunlight but the building would also benefit in terms of heat absorption and reduced heat gain. In general the system is useful for interiors which require directed light and are not affected by contrasts. This could be suitable for atria, large markets, shopping malls or restaurants to place dynamic daylight accents and highlight certain spots. If a more even and diffuse light distribution like in train stations, etc. is required an additional adaptive light diffusor has to be thought of.

Simulation versus prototypes

With the current possibility to easily and cheaply manufacture functional prototypes and the ongoing tendency of more, relatively cheap, user friendly but none the less fairly accurate 3-D printing technologies like FDM printers being released on the market there is a great chance that we might face a renaissance of physical testing rather than simulation only approaches.

OUTLOOK

To finalize the research the measured results will be fed back into the digital environment to close the circle but also to have a more complete design tool. In more practical terms sensing and actuation and the digital interface should be thought of as well as more material research for an actual application has to be done. The requirements for a high degree in precision in redirecting sunlight needs to be further considered. The extreme converging mode of the lens and bundling the light into one spot might not be applicable for lighting the interior but could be interesting in combination with photovoltaic as a concentrator system while the space underneath is less frequented or occupied by the inhabitants. The photovoltaic elements could be mounted as a relatively small device close to the ceiling and would therefore not disturb the flow of light otherwise. It would be also possible to employ a more expensive but highly efficient photovoltaic cell since the surface area is small while being more protected from any outdoor influences like dust and rain. Next steps will also include research in smart material application together with the Functional Devices research group of the Department of Chemical Engineering and Chemistry at the TU Eindhoven in order to investigate the possibility to develop a similar functioning system without any moving parts involved.

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[2] <http://www.solemma.net/>

[3] <http://www.vray.com/>

[4] <http://www.ise.fraunhofer.de>

[5] <http://www.photolux-luminance.com/>