Adaptive liquid lens and sunlight redirection

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Adaptive Liquid Lens and Sunlight Redirection

Florian Heinzelmann, Telesilla Bristogianni
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The paper describes a novel system to alter and redirect sunlight under large roofs with the help of a liquid lens system. Focus lies on the computational design, testing, measurement and evaluation of the performance of a physical prototype. The results in terms of daylight and illumination of the interior, as well as the possibility for sunlight redirection, lead to an array of adaptive natural light spotlights, which are rather promising. The journal article is an extension of previously reported work[1].

I. INTRODUCTION

Daylighting, the supply of quantitative and qualitative adequate natural indoor lighting in combination with protection from overheating, is a well-researched and applied design approach when it comes to vertical façades, especially regarding office and residential buildings. Here static as well as adaptive solutions like light shelves or reflective, retractable louvers can be found applied in the built environment and various products are available. However dealing with large roofs where the horizontally laid out functions underneath cannot be sufficiently lit by the vertical façades, the roof structure and/or its openings will become the main surfaces which have to transmit daylight. This is relevant for buildings like stations, airports, sports facilities, museums, big atria or trade fair buildings. Since the position and orientation of a building in relation to the sun continuously shifts during the day and seasons, weather and climatic conditions are varying, programs and functions may change over time, static designs will not provide the best performing solutions. Therefore it is necessary to enhance a building's performance with adaptive solutions which are able to react in real time to the changing conditions. The research done for the Adaptive Liquid Lens and Sunlight Redirection is aiming to provide a solution for both application for large roofs and being able to adapt to changes in real time regarding sunlight conditions while providing natural light in the interior wherever it is required.

2. PRINCIPLE

The adaptive lens and sunlight redirection system consists of two major components. Firstly 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

▼ Figure 1: Objective of the adaptive liquid lens and sunlight redirection system.

adaptive lens. The adaptive liquid lens is located underneath the sunlight redirecting mirrors. 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 [2] and Snell's law [2]. By computationally testing different clear and transparent liquids available on the market the refraction effect is more or less strong according to their respective Index of Refraction.

▲ Figure 2: Description of the proposed system.

3. DESIGN APPROACH

The design approach consists of six steps. (1) Physical principles (2) Associative sectional (2-D) models (3) Associative 3-D models (4) Simulation (5) Prototype (6) Prototype measurements and evaluation.

3.1 Physical principles

In order to apply physical principles like Snell's law or Fresnel's equation [3] 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. For the case of the liquid lens Snell's Law is most relevant.

Index of Refraction:

$$n = c / v$$

n = refractive index

c = speed of light in vacuum

v = speed of light in a medium

Snell's Law:

$$\sin\theta_1 \cdot n_1 = \sin\theta_2 \cdot n_2$$

θ_1 = angle of incidence, measured from the normal of the boundary

θ_2 = angle of refraction, measured from the normal of the boundary

n_1 = refractive index of first medium

n_2 = refractive index of second medium

▲ Figure 3: Snell's Law.

3.2 Associative sectional (2-D) models

The relevant physical laws were translated into associative 2-D sectional drawings of a light converging/diverging lens system and mirror system in order to understand the capability of the system and how it performs 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 and lower 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 by applying the formulas and angular calculations within the lens and made visible via a bundle of lines to serve as design and early evaluation tool. Here it became clear that due to the potential weight of the contained liquid a lower flexible membrane is not suitable. Nonetheless, light can still be altered sufficiently by only changing the upper membrane. However the change in altitude angles of the sun leads to a change of the focal point of the refracted light and it also 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 in or out due to the resulting change of the focal point in relation to the sun's changing

▼ Figure 4. Left: Adaptive prisms for light redirection. Right: Adaptive lens' possibilities, grasshopper output of change of focal point.

altitude. Due to 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 more promising in terms of being able to redirect light under a greater variety of altitude angles. In order 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. Since it became clear that a light redirection device would have to follow the sun’s azimuth, thus only the altitude sun angle is relevant, the 2 dimensional, sectional approach was continued. Using an array of mirrors instead of one large single element poses several challenges in terms of overshadowing each other and being able to redirect sunlight in different quantities according to the sun’s altitude angle. In order to find optimal configurations, testing and optimization of sizes and mirror distances was done with the Galapagos genetic algorithm solver [4]. The initial results were not satisfactory in terms of amount of daylight redirected due to overshadowing especially at lower sun altitudes and it turned out that there is no universal system which works equally well in every situation.

▼ Figure 5: Grasshopper study on the percentage of sunlight redirected perpendicularly to the floor according to different scenarios based on prisms or mirrors.

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.

By applying Galapagos 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 within a range or Δ of thirty degrees a hundred percent. It is then a 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 sun altitude.

▼ 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
ALTITUDE ANGLE	DST	off	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
	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
	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
	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
	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
	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
	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
	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
	Jan-Dec	49,57	-	9,64	11,28	22,38	9,55	18,93	7,03	13,94	5,90	11,70	4,77
		2,26	4,48										

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
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
Dec	1,58										

Data collected from: Climatedata.eu, <http://www.climatedata.eu/climate.php?loc=gmxx0087&lang=en>

▼ Table 2: Relation between mirror's width and delta of sun altitude angles which are redirected perpendicularly to the ground a 100%.

Percentage of entering perpendicular light in relation to the mirror width											
Mirror width (m)	0,17	0,18	0,19	0,2	0,21	0,22	0,23				
	Angle (°)	Angle (°)	Angle (°)	Angle (°)	Angle (°)	Angle (°)	Angle (°)	Angle (°)	Angle (°)	Angle (°)	Angle (°)
Panel rotation: -59°	1	1	1	1	1	1	1	1	1	1	1
	2-32	4-36	3-5	3	3	3	3	3	3	3	3
	39	42	7-39	6	6	6	6	6	6	6	6
	45	47	80	44	10-41	100	9	8	8	8	8
	51	53	70	50	47	90	13-44	12	11	11	11
	57	59	60	55	52	80	49	15-46	14	14	14
	63	64	50	60	57	70	54	51	18-48	100	100
	65	46	48,4	50	62	60	59	70	56	53	50
No. of mirrors: 13					65	53,6	63	60	60	57	80
							65	56,2	65	61	70
										65	61,4

Percentage of entering perpendicular light in relation to the mirror width

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

3.3 Associative 3-D models

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, but also to have a geometrical input for later daylight simulations. Regarding visualization of the redirected sun rays the solar tool of the Rhino Grasshopper/Diva plugin by Solema [5] proofed to be valuable. However during the research a discrepancy between the sun vectors generated by the solar tool and other digital daylight systems in altitude and azimuth angles up to fifteen degrees were discovered and discussed with software developers and eventually was solved in the 2.1.0.0 update. This is insofar important since smart and adaptive geometries which are laid out and designed to perform under rather specific conditions will not match in terms of design prediction and simulations or validation. The Rhino modelling environment was not only chosen for the comfortable integration of the parametric grasshopper design tool but also due availability of several plugins like DIVA which make the seamless integration of Radiance daylight simulations possible.

▲ Figure 6: Grasshopper study on the percentage of sunlight redirected perpendicularly to the floor according to the sun altitude.

3.4 Simulation

The simulations were done via Diva/Radiance and the V-Ray renderer [6] 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/m^2 . This would enable to check the performance for actual conditions and requirements as stated in e.g. building codes. However the various simulations done proofed to be not accurate since Radiance for windows is not able to calculate optical effects with dielectric material properties properly [7]. This has to be done in the Linux environment with the help of a photon mapping module, which was developed by the Fraunhofer ISE [8]. However 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. As point of reference contemporary

▲ Figure 7: Radiance for windows luminance simulation. Convex and Concave Lens do not display the predicted difference.

render engines such as V-Ray are able to calculate caustic effects [6] 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. Light measuring instruments are readily at hand, the measured results are less prone to misinterpretation and a physical prototype gives much more insight and inspiration for further research. One should also not underestimate the fact that having something tangible immediately increases the credibility also to a larger audience.

3.5 Prototype

The initial prototype consists of transparent plastic petri dishes and clear household kitchen foil and displayed the expected optical behavior as any lens would. Due to the intended use and nature of household kitchen foil namely, being mainly plastically deformable and not elastically, the initial prototype was not adaptive yet. Later prototypes were built with the focus on adaptability in terms of lens membranes and the elasticity and sunlight redirection possibilities of the mirror system.

During the design process for the prototype, research was done for lens diameters, change of volume and therefore weight on the roof for a 1:1 case. In general it can be concluded 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 of converging or diverging light. By studying these parameters it was decided that a lens with a diameter of 1m meter would be optimal for many applications in terms of weight and required volume change within the lens.

▲ Figure 8: Images of the first proof of concept prototypes.

The final prototypes which serve as proof of concept and are used for daylight performance measurements were manufactured in the scale 1:10. 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 was applied on the rotatable ABS fins. The membrane for the lens turned out to be the most difficult part to make. After several unsuccessful material tests a self-cast and baked Polydimethylsiloxane (PDMS) membrane provided by Michael Debijs at Functional Devices research group of the Department of Chemical Engineering and Chemistry was used.

▲ Figure 9: Volume change required for the convergence and divergence of light in relation to the room height.

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

The rest of the parts like syringes and hoses are standard shop ware. As a liquid water with an Index of Refraction of 1.33 [9] was used. Other liquids like colorless and transparent oils are also thinkable. However it is important to consider those for the prototype as well as for the final product under several viewpoints.

- **Costs:** Some of the found optical liquids are even in small amounts extremely expensive.
- **Combustion:** Intended for the built environment a liquid used needs to fulfil requirements in terms of fire regulations.
- **Index of refraction:** Apart from a few exceptions, Liquids with a higher Index of refraction also have a higher viscosity. That means that less pumping and change of volume, thus lens' change in shape is required in order to produce a similar optical effect. However the pumper needs to be stronger.
- **Material Interaction:** Not only should the membrane have a similar transparency and index of refraction as the liquid but it is also important that one material is not reacting with the other and the liquid dissolves the membrane.
- **Phase change:** Since the liquid and the membrane are at the outer layer of the building it is important that the liquid is not freezing or boiling at common outside temperatures during winter and summer. Otherwise an additional layer would be required to protect the systems.

▼ Table 3: List of transparent liquids.

Material	Index of refraction at 20 °C	Viscosity (mPa*s)	Density (Kg/m³)	Freezing point (°C)	Flash point (°C)	Solubility in
Water	1,33	1 (at 20° C)	1000	0	Not flammable (Boiling point 100)	Water
n-Butanol	1,399 (at 20° C)	3	810	-90	35	Water
Glycerol 60%	1,412	10,68	1153	-37,8	160 (solid glycerol)	Water
Calcium Chloride 32 %	1,418	4,035	1303,6	-49,7	Not flammable	water, acetone, acetic acid, ethanol
Ethylene Glucol	1,438	16,1	1113,2	-12,9	111	Water
Calcium Chloride 40 %	1,44	8,99	1395,7		Not flammable	water, acetone, acetic acid, ethanol
Glycerol 80%	1,443	59,9	1208,5		160 (solid glycerol)	Water
Carbon Tetrachloride	1,45	0,95 (at 20° C)	1586,7	-22,92	Not flammable	Alcohol, ether, chloroform, benzene
Mineral Oil	1,46	34,5 (at 40° C)	≈ 800	-30	depends: 129-195	In volatile oils, ether. Insoluble in water, alcohol
Safflower Oil	1,466	50 (at 23° C)	880	-17	167	Alcohol (80° C)
d-Limonene	1,47	0,9	841,1	-74,35	50	Nonsoluble in water
Castor Oil	1,475 (at 25° C)	615-790 (at 25° C)	961	263,2	285	Alcohol (ethanol)
Silicone oil	1,50-1,52	10 (at 25° C)	930	-55	316 (Boiling point: 140)	slightly soluble in water
Wintergreen Oil (Methyl Salicylate)	1,528 (at 25° C)	1,535	1174	-8,3	101	Alcohol, paraffin oil. Slightly in water

Technical system

The adaptive liquid lens at the current prototype is operated via hoses and attached syringes. When considering a final design to be placed in a building several other aspects are important.

Actuation:

It is intended to have several lenses and mirrors working together but the system should be able to address each of them individually in order to have an interplay of several lens systems. This could be achieved via a hydraulic system where the liquid reservoir and pump is an extra unit which is stored at a central location. All of the lenses would be connected with a system of pipes and individual change of the lens geometry would have to happen via individual valves either shutting the lenses off the hydraulic array or changing the hydraulic resistance accordingly. This seems not to be the most efficient way due to the increased installation effort because of the amount of pipes as well as hydraulic, automation control engineering. It not only needs to take into account pipe lengths and resistances due to flow of liquids in curves, but the whole hydraulic interaction with individual valves and resistances as a whole. Therefore it is aimed to have a system of individual and hydraulically not connected lenses (decentralized) where actuation and storage of liquids is integrated in the perimeter of the lens body. That would also make maintenance less of an effort.

▼ Figure 11: Liquid lens with actuation and storage of liquids integrated in its perimeter.

3.6 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). For the simulation of the clear sunny sky, a Solar Simulator was used, providing directional light, while for the overcast sky, an Artificial Sky Simulator was employed, to achieve diffuse lighting

▲ Figure 12. Left: Solar Simulator at a 90° altitude (Test 1). Middle: Solar simulator inclined at a 30° altitude (Test 3). Right: Set up for Test 4, using the Artificial Sky Simulator.

conditions. Through all test series, illumination measurements were done using a Hagner Digital Luxmeter EC1 and lumination pictures were taken with a Canon EOS 60 D and further processed in Photolux 3.2. [10]

▲ Figure 13. Left: Test 1 settings, solar simulator at a 90° altitude. Middle: Test 2 settings, solar simulator at a 90° altitude. Right: Test 3 settings, solar simulator inclined at a 30° altitude.

Clear sky with sun, Test 1 & 2 set up

The first two series of tests (Test 1 & 2) focused on the performance of the adaptive liquid 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: $0,5 \times 0,5 \times 0,35$ m, Test 2: $0,7 \times 0,7 \times 1$ m) with a circular opening at the center of their top surface for the 10 cm diameter liquid 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 1 m diameter liquid lens in a 3,5 m and 10 m high room respectively.

Test 1 & Test 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. Comparing the two room scenarios and scaling up the results to 1:1, it is confirmed that a lens of 1 m diameter is more efficient over a 10 meter high room than a 3,5 meter room, as previously estimated. To be more specific, in the case of the 1 m box, the removal of 55 ml of water from the lens in neutral mode causes a circular lit area on the floor of 0,46 m diameter while the addition of 12 ml produce a focal point on the floor of 0,01 m diameter (in full scale the values are 10 m, 55 L, 4,6 m, 12 L 0,1 m accordingly). At the 0,35 m high box however, when an almost equal water volume (58 ml) is removed from the neutral lens, a lit area of approximately half diameter (0,22 m) is produced. Furthermore, in order to achieve focused light on the floor at a point of 0,005 m diameter, 26 ml of water need to be added to the neutral lens (in full scale the values become 3,5 m, 58 L, 2,2 m, 26 L and 0,05 m accordingly).

At the concave 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

▼ Figure 14: Differences in the quality of shadows from the diverged to the converged mode of the adaptive liquid lens.

periphery inside the box. On the other hand, when the light is focused at the floor level, the flux density is so high that in fact the focal point acts as a point light source itself, casting hard shadows by the figures. The choice of a white shiny material for the floor surface is contributing to the intensity of these hard shadows as a significant amount of light landing on the floor gets specularly reflected. Finally, at the lens' neutral state it is observed that the incoming light is projected back to the lens' surface.

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 [11], the flux density will be 6.940.000lux at the center and 4.000lux at the periphery, when the liquid lens is at the focused mode. Even more, a 99,96% decrease of the brightness levels is observed at a distance of 0,1m from the center in the case of the 0,35m high box (1m at full scale). 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 [12]. Further analysis needs to be conducted to evaluate the presence of discomforting or blinding glare in the interior in regard to the different lens configurations. Moreover, the tests should be repeated in order to determine the reduction of these contrast ratios when a floor of increased surface roughness and darker color is selected, to increase the diffuse reflection (light reflected in all directions) and minimize the specular one (light reflected at a defined angle).

▼ Figure 15: Test 1, comparison between the diverged and converged mode.

▲ Figure 16: Test 2, light diverged via a concave and a convex configuration of the adaptive liquid lens.

Test 3 set up

Test series no. 3 examines the effectiveness of the sunlight redirection system on a clear sunny day. For these tests, the 0,5*0,5*0,35m box from test 1 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 according to the Grasshopper/Galapagos models. The system was placed over the liquid 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 & Test 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. Given the fact that for an opening of 1m diameter and a 3,5m high room, a gradual angle difference between the first and the last mirror of 5,8 degrees increases the directly lit area by 400%, it can be derived that even minor deviations of the mirrors from the correct inclination can direct the light in a non-desired direction. In addition, it is assumed that deviations from the ideal light redirection model are also caused by the material used for the mirror surfaces of the prototype. The 3M™ Solar Mirror Film 1100 is not producing a perfect specular reflection but is in fact scattering a small portion of the incident light. The light scattering can be further enhanced if the film is not properly attached over the ABS lamellas, meaning that parts of the film are not stretched forming a perfectly straight surface but tend to curve. The imperfections at the rotation mechanism are also responsible for the presence of 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.

It was also observed that although the incoming redirected light has a circular footprint on the floor, within the bright spot itself, there is a

▲ Figure 17: Test 3, different lens configurations.

difference in the levels of illumination which should not occur. This can be partially explained by considering that the inverse square law is applicable for the solar simulator and therefore light is expected to be dimmer as the light source (the light reflected from the mirror) is farther from the floor (13cm farther in our case). This phenomenon is not to be expected in reality where such differences in distance are considered negligible regarding the strongly directional light emitted from the sun.

Light redirecting possibilities

The prototype showed that initial expectations in terms of light redirection capabilities of the systems were by far exceeded. 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 which would be 5m x 5m in 1:1 scale. 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, the larger the distance will be which the redirected light can travel, thus the range and performance increases. It is also important to note that due to the height of the redirection device, the area of illumination is more

▼ Figure 18: Adaptive daylight in the interior.

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 liquid 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 3,1% 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 [13]. Taking into account that the light absorption coefficient of water for violet light (380nm wavelength) is $0,00011 \text{ cm}^{-1}$ and for red light (725,5nm wavelength) is $0,01678 \text{ cm}^{-1}$ [14] 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 however, the occurring light absorption will increase due to the 10 times higher water depth. Indeed, calculations show that 0,35% of violet light and 41,77% of red light will be absorbed by the water volume. This will result in a total reduction of the incoming light. 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 [15]. Of the radiant energy emitted from the Sun, approximately 50% lies in the infrared region [16]. Regarding that 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 according to the surrounding temperature and reduces the heat gains as the penetration of heat is delayed.

Finally, in regard to the quality of the incoming light, it was found that trapped air in the water volume affects the uniformity of the incoming light as the occurring air bubbles cast shadows on the floor surface. Although in full-scale this phenomenon is expected to be less apparent, the minimization of the air content is considered important.

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 liquid 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 it can be concluded 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, a typical flux density at ground level on a cloudy winter day of 4000lux [11] is considered and related 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 liquid lens is present, and in 116lux and 79lux respectively when the sunlight redirection system is added.

4. ALTERNATIVE SOLUTIONS

Choosing for an adaptive lens that is based on the movement of liquids naturally raises questions regarding the imposed load on the roof and the absorption and quality of light reaching the interior, and is paired with construction complications related to leakage and the vulnerability of the exterior membrane. Thus alternative solutions based on multiple moveable lenses or on smart materials were considered and compared to the initial proposal.

4.1 Interaction of multiple lenses

This proposal is based on the principle of zoom lenses in photographic cameras. These usually consist of multiple lenses of different focal lengths that are moved close or apart of each other in order to alter the size of the light-beam or to focus the light.

Likewise, the proposed system is based on 2 or 3 interlocking glass lenses of 1m diameter, with the upper one being fixed while the rest have the ability to move downwards. Several scenarios were examined with parameters the number of moving lenses and the focal length of the lenses. For the assessment of the scenarios, a 2D parametric file was built in Grasshopper.

All the studied cases proved that in order to achieve considerable changes between diverged and converged light, the interior lens has to significantly descent. Specifically, in a room of 10m height, to alter the light from parallel to converged by 3 times more than the initial diameter, at least 0,9m of downward movement is required. This causes problems regarding the height of the total system and more importantly the ability of the system to work when the incident sunlight is not perpendicular to the ground. A 1m distance between the two lenses could lead to significant light loss when the light enters in a shallow angle. In some of the scenarios it was also observed that there was no continuous transition from converge to parallel to diverge mode or that the incoming light in the parallel mode

would be reduced in diameter. But more importantly the additional height in comparison to the thinner liquid lens also impairs the possibility to redirect light because the rays will illuminate the light pipe rather than the interior.

Regarding the weight of the system, this solution is much heavier than the adaptive liquid lens proposal, with a set of two glass lenses weighing up to 300 kg and a set of three 600kg. Acrylic glass was also considered, resulting to a system of 2 lenses that weigh 135kg. To further reduce the mass, the system was calculated using acrylic Fresnel lenses of the same focal length. The mass was reduced to 82,5kg which is still 12,5kg more than the maximum mass of an adaptive liquid lens of 1m diameter in a 10m height room.

The above limitations and disadvantages led to the discard of the multiple lenses approach.

▼ Figure 19: Grasshopper calculation of light redirection for a system of two moving lenses.

4.2 Smart materials

Further research led to the investigation of the possibility to use smart materials to achieve the convergence and divergence of sunlight and the redirection of the sunbeams. Ideally, the same smart material should perform all the above functions, minimizing therefore the total mass of the lens, its' detailing and the energy costs required for its operation.

Extensive research has been conducted regarding tunable focus micro-lenses that find applications in cameras for cell-phones, endoscopy systems, etc. The apparatus are divided in two main categories related to the method they adjust the focus: by changing the refractive index and by changing the curvature of the lens. Changes in the refractive index can be achieved with liquid crystals and the application of voltage [17] while for the change in

curvature different systems exist grouped in 4 categories according to their cause of change: fluidic pressure (actuators: syringe, servo-motor, piezoelectric, artificial muscle, voice coil actuator; thermo-pneumatic [18,19]), thermal effect, electrowetting, and dielectrophoresis. In many of these research projects smart materials such as thermo-stimuli hydrogels [20] are used to change the volume of the liquid in the lens, resulting thus to a change of its curvature.

Research on hydrogels is also conducted at the Department of Chemical Engineering and Chemistry at TU Eindhoven with the aim of constructing responsive surface topographies [21]. Hydrogels are polymer networks that can absorb hundreds of times their mass in water when triggered by a specific change in the temperature, light conditions, pH, humidity or electric field. The swelling capacity of the hydrogels can be controlled according to the degree of crosslinking of their network, therefore the researchers aim at creating inhomogeneous surfaces of different crosslinker distributions along the hydrogel film, which will non-informingly swell, forming thus 3D microstructures.

In consultation with Prof. Dr. Broer and Dr. Debije a concept for an adaptive lens and redirection system out of light responsive hydrogels based on poly (*N*-isopropylacrylamide) (pNIPAAm) has been developed. When the lens' surface temperature is lower than the critical (34°C), it remains flat, while when incident light is heating it over the limit, it swells forming a fresnel lens that diverges the sunlight. The sunlight redirection system consists of triangular pNIPAAm beams with a highly reflective foil attached to one of their surfaces. According to the changes in the incident sun-angle, the hydrogel is expected to swell or de-swell changing the angle of the film and thus the redirection of the sunlight. Next steps should include the development of the smart material proposal together with the Functional Devices research group of the Department of Chemical Engineering and Chemistry at the TU Eindhoven. Particularly interesting will be to investigate the possibility to develop a similar functioning system without any moving parts involved.

▼ Figure 20: Adaptive lens and sunlight redirection system proposal based on light responsive hydrogels and shape-changing polymers.

Angle change required for the perpendicular redirection of a sun angle range of $63^\circ = 31,5^\circ$

Angle change required for the perpendicular redirection of a sun angle range of $30^\circ = 15^\circ$

As previously mentioned the smart material research is currently in the concept phase and further investigation in collaboration with fundamental sciences as well as industrial partners need to be conducted.

4.3 Energy production

The extreme converging mode of the lens and bundling the light into one spot may 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 far less while being more protected from any outdoor influences like dust and rain.

▲ Figure 21: Adaptive sunlight redirection system proposal based on light responsive hydrogels and mirror films.

▲ Figure 22: Adaptive lens that converges light for energy production when the room is not inhabited and converges light when the user is present.

5. CONCLUSION

Assessment of the adaptive liquid lens and sunlight redirection

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.

However, concerning the high contrast ratio observed in some of the tests and the probability of glare, it is required to evaluate this further. 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 suboptimal. Here other non-adaptive solutions have to be evaluated to understand at which square meter threshold of glazed roof surface daylight autonomy is guaranteed. 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. Therefore by applying the system at the more southern hemisphere it would not only be more effective in terms of direct sunlight but also 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 diffuser has to be thought of.

Alternative solutions

The multiple lenses solution, although simple in concept, requires complicated engineering and over a meter height, in order to work. Its increased weight and inability to work with low solar-incident angles lead to the discard of the proposal. Implementing smart materials shows a much more promising path, but this proposal is still in a very experimental stage and there are only indications that these light responsive hydrogels will have the desired results once applied in a component of architectural scale. The two alternative approaches which were studied in addition to the Liquid Lens, in fact confirm that the current approach with contemporary technology at hand is a feasible way for product development. To finalize this research work on the adaptive liquid lens and sunlight redirection system, 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, actuation and the digital interface should be thought of, as well as more material research for a product application has to be done. The requirements for a high degree in precision in redirecting sunlight needs to be further considered.

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 and thus being applied by a larger group of users, there is a great chance that we might face a renaissance of physical testing rather than simulation only approaches. It will be interesting to closely watch the coming years due to the fact that manufacturing in form of 3-D printing technology will become common property whether there is going to be a shift in design practices from simulating towards prototyping or even of prototypes becoming instantaneously the actual product.

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Florian Heinzelmann¹, Telesilla Bristogianni² and Patrick Teuffel³

¹Eindhoven University of Technology, Department of the Built Environment, Unit of Structural Design, Chair of Innovative Structural Design, f.heinzelmann@shau.nl

²SHAU Architects, t.bristogianni@shau.nl

³Eindhoven University of Technology, Department of the Built Environment, Unit of Structural Design, Chair of Innovative Structural Design, p.m.teuffel@tue.nl