Title: MULTI-ELEMENT DEVICE

Abstract: The invention relates to a solar tracking system embedded in a flat package which exhibits no mechanical motion outside its form factor, and which can be compactly integrated in a fixed position into walls, roofs, etc of buildings or in free-standing structures. In addition to solar energy collection for the generation of electricity, the invention can be used for collecting and transmitting solar energy for heating and lighting applications. The invention employs a multi-element pointing array comprising at least two direction-critical elements capable of receiving and/or transmitting electromagnetic or acoustic radiation, wherein each element in the array is adapted to exhibit a pointing and/or alignment motion by rotating about one, two or three axes and moves in synchronism with other elements in the array, where at least two of said elements are directly or indirectly linked to at least two physical structures that can translate and/or rotate relative to each other.
MULTI-ELEMENT DEVICE

Field of the invention

The present invention relates to a solar tracking system embedded in a flat package, which exhibits no mechanical motion outside its form factor, and which can be compactly integrated in a fixed position to constitute parts of walls, roofs, etc of buildings or in free-standing structures. In addition to solar energy collection for the generation of electricity, the invention can be used for collecting and transmitting solar energy for heating and lighting applications. More generally the present invention relates to multi-element pointing arrays for receiving and/or emitting and/or reflecting electromagnetic or acoustic radiation.

Background art

With the exception of phased-array type devices, direction-critical elements in the form of antennas, floodlights, laser projectors, etc are generally dependent upon being mechanically aligned in a desired direction, henceforth termed the pointing direction. In many cases, this direction shall change over time and the mechanical alignment must be re-directed accordingly. Depending on the application, the mechanical alignment may require a mounting support capable of rotation about one, two or three axes. One-axis, or single-axis mounts can adjust the pointing direction in a plane. Two-axis, or dual axis mounts can select any pointing direction in space, whereas three-axis mounts in addition can define the axial rotation angle along the pointing axis. Thus, if polarization-sensitive and similar antennas are excluded, mounts are typically of either the single or dual axis type. The passive gain of an antenna or the performance of
a direction-critical element is generally a function of the effective area presented by the element in the pointing direction. In many applications it is therefore desirable to make the direction-critical element as large as possible, while remaining compatible with other requirements related to available space, maximum cost, weight etc. This often leads to conflicting demands on design, since large elements typically imply large bulk and weight and in turn lead to mounts that are large, heavy, costly and consume much power to move.

The above considerations apply in a wide range of real-world situations, particularly where emission or reception of electromagnetic radiation (microwave, radio, optical, far infrared) is involved, but also in acoustics and certain specialized applications. In many cases, the cost and size considerations are less important than achieving desired importance. Examples are military and scientific applications, where very large antenna structures on alignment mounts are well known. However, there exist important areas of applications where practical or economic issues related to achieving directionality in large-area emitting- or receiving structures decide whether a particular installation shall be built or not. One example is in harvesting energy from sunlight, which shall be discussed in some detail below.

The present climate debate has spurred a strong interest in enhancing the cost efficiency of solar energy collection methods. This is intimately related to the transition that needs to take place from small scale, price insensitive, specialized applications to a mainstream energy commodity market where cost issues are decisive. Two technical issues are of particular
importance in this context:

i) The areal energy density in sunlight is such that large collector areas are required to achieve energy harvesting on a scale that is relevant for solar energy to make an impact in the energy commodity market.

ii) The sun moves over a large angular distance in the sky during the day.

Taken together, these imply that large collector structures must be able to track the sun in order to be efficient. This provides an example of the problem discussed above. As has become increasingly clear during the latter years, employing large area first generation solar photovoltaic panels in a fixed position, i.e. not tracking the sun, is no long term solution for reaching a competitive position vis a vis traditional energy sources. On the other hand, conventional structures that enable large-area flat photovoltaic panels to track the sun are generally heavy and unwieldy, and require considerable power to perform tracking.

Although improvements in the photovoltaic efficiency are taking place and energy harvesting is sought enhanced by large flat-panel devices that are mounted on sun trackers, it appears that significant change in the field of low cost photovoltaic solar power can only be expected when third generation technologies come on line. These are presently expected to encompass ultra low cost, thin film large area photovoltaics or some form of concentrating optics. The former has not yet documented that it can offer an adequate combination of low cost, reliability/endurance and conversion efficiency, and may
take many more years to mature. The latter relies on collecting sunlight from a large area, using readily available and low cost materials and concentrating the light upon a much smaller area. Such methods have been around for a long time but have as yet not made a major impact. Research in the field began in earnest in 1975, following the 1973 oil crisis. The principle is quite straightforward: Use lenses or mirrors or both to concentrate sunlight onto a small area to increase the energy density, and position the energy harvesting structure at that point. For photovoltaics this leads to a reduction in the amount of required photovoltaic material, and a higher concentration of sunlight may also under the right circumstances enhance the photoelectric conversion efficiency. The concentration ratio can vary, from 2 - 20 suns for one-axis trackers to hundreds or thousands of suns for the most advanced 2-axis systems (one sun is the unconcentrated solar flux). This will reduce the photovoltaic (PV) area by the concentration factor.

In order for concentrator devices to be competitive, sun tracking is necessary, and for optimum performance 2-axis tracking is absolutely necessary. The tracker designs that have been pursued to date, at least the 2-axis ones, have generally involved very heavyweight structures. Concentrator designs often include tens of square meters of lens or mirror arrays, weighing hundreds of kilograms and more. In addition there are problematic issues relating to maintenance, reliability and stability, e.g. in bad weather conditions such as high wind speeds (in most cases, systems cannot operate in wind speeds exceeding 20 - 25 m/s). Furthermore, traditional pedestal-type trackers cannot be positioned close together in large scale solar farms, due to mutual shadowing and turbulence
effects. In order to convey an understanding of what is involved in practice, Figs. 1a-h show some examples of prior art pointing element configurations, with emphasis on solar energy harvesting: Fig. 1a shows a 25 kW two-axis tracking and concentrating module by Amonix at Nevada Power in Las Vegas. Fig. 1b shows another two-axis tracking and concentrating module (FLATCON type) by Fraunhofer ISE. Fig. 1c shows an installation by Pyron Inc., where the whole two-axis tracking array is floating on water, in an attempt to avoid some of the problems associated with large pedestal-type mounts. In other approaches to the tracking problem, simplification has been sought in reducing the tracking precision requirements by employing extended area photovoltaic cells in conjunction with concentrating optics that produce relatively large focal spot sizes. A typical example is shown in Fig. 1d (Soliant Energy, Inc.), where photovoltaic cells capture energy along a focal line in parabolic trough concentrators that track about a single axis only. Such solutions are not ideal since they either require significant amounts of photovoltaic material or waste solar energy through imperfect tracking.

Much of what has been said above about tracking and photovoltaics applies for other types of solar energy harvesting as well, e.g. collection of light for illumination purposes. Figs. 1e, f show examples of this: In Fig. 1e (from US Patent Application US2004/0118447 A1, Muhs et al.), a pedestal-mounted tracking parabolic concentrator collects light onto an optical fiber. In Fig. 1f (from US Patent Application US2002/0148497 A1, Sasaoka et al.), an array of lenses on a sun-tracking mount on a pedestal images sunlight onto a plurality of optical fibers which transport light to a point of use
elsewhere.

Thermal energy generation from sunlight has a long history, generally associated with low technology and moderate temperatures, e.g. generation of hot water for domestic use. In such applications, it is relatively uncritical to perform precision alignment of the solar energy collector. However, it can confidently be predicted that in the future higher demands on cost efficiency, combined with novel technological opportunities for conversion and exploitation of thermal energy shall lead to more stringent demands on solar collector efficiency and thus concentrator devices and tracking systems also. Given the possibilities that can be envisaged on the basis of the present invention, this shall apply not only on a utility scale in multimegawatt plants, but also on small scales, e.g. in households and small enterprises where a flat package that has no externally moving parts and that can be mounted in a fixed position, with high tolerance to wind loads and bad weather can be expected to be of considerable interest.

Summing up so far: Present-day two-axis trackers that can present a large area in any given pointing direction typically operate elevated from the ground, require large and heavy mounts, and need to be surrounded by ample space for manoeuvering. In the context of solar energy harvesting, they are clearly not suited for roof-tops and definitely not for building integration. Yet there exists a very large need for practical solutions where solar energy harvesting, be it in the form of electricity generation, lighting or heating, can be integrated into buildings and other structures in a way which is economic, functional and aesthetically satisfying.
One approach which would lower the height profile of a large area tracker, in particular of the two-axis type, is to substitute a single large directional element by an array of smaller directional elements that are positioned side by side and can track in parallel. This could be done on a flat frame which remains stationary and is easy to integrate into a static structure such as a wall or a roof on a building. By proper weather proofing and modularity such flat arrays could displace roofing or siding materials and represent economically attractive solutions for solar energy harvesting in future integrated building designs.

There are a number of technical and economic issues related to flat arrays which until now have limited their usefulness. One obvious limitation is that a fixed flat frame presents a smaller projected area when viewed from progressively more skewed angles, an effect which alignment of small directional elements on the frame cannot compensate for. Note, however, that free-standing pedestal-type trackers that point optimally towards the sun face a different problem: They require ample free space around them for manoeuvering and reducing shadowing and turbulence effects. Thus, a rule of thumb recommends a distance between such trackers at least 4 times the motion-related footprint of each tracker, reducing the areal density on the ground by an order of magnitude or more. In contrast, pointing arrays confined in a stationary frame as taught in the present invention lend themselves naturally to dense side-by-side packing on walls, roofs, etc. Such a side-by-side arrangement can exhibit a high integrated energy capture during the day, provided that the stationary frame is oriented such that it does not deviate much from normal incidence of sunlight.
at noon. Comparison with a frame which tracks the sun so as to maintain normal incidence throughout the day shows that with diurnal insolation typical in many representative locales in the northern hemisphere, taking into account atmospheric attenuation and shading effects that often occur at low sun angles, the former may often capture up to 80% of the energy of the latter.

All told, issues relating to cost and practicality rather than the projected area effect are probably the main reasons why fixed frame array solutions as yet have found very little use in practical implementations, despite acknowledged advantages such as low profile, high wind tolerance, and convenient integration into buildings, etc. These advantages are brought forward by inventors Ansorge et al. in WO 2006/005303: "Device for concentrating light, particularly sunlight", where they teach the use of an array of adjacently arranged mirrors to concentrate light upon a receiving object, cf. Fig.1g:

Each mirror can be tilted about two axes by means of micro-actuators driven by hydraulic or piezoelectric means. As described, these micro-actuators need to be individually controlled, and it appears obvious to the skilled person that the overall design taught by Ansorge et al. shall incur significant production costs, in particular when the number of mirrors becomes large. In US Pat. 4,102,326 W.T. Sommer describes a solar collector having a central radiation receiver and a field of mirrors which are mechanically linked to track the sun and reflect solar radiation onto the radiation receiver. Sommer recognizes the advantages of employing a large number of collectively controlled, smaller mirrors rather than a single large one, and has designed a mechanical system that compensates for the alignment differences that are
required for mirrors at different positions in the field of mirrors to reflect convergent beams onto a single small target located nearby, i.e. at a distance which is comparable to the extent of the field. As is apparent from US Pat. 4,102,326, the required mechanical linkages and their relationships are complex and stringently defined, with limited relevance in other types of applications and none as a universal principle for parallel alignment of arrays of direction-critical elements. In US Pat. Appl. US 2004/0246596 Al A.H. Dyson et al. describe a solar panel comprising a plurality of concentrating solar modules, each module comprising a polygonal Fresnel lens and a photovoltaic cell and being able to rotate in synchronism with the others about two axes by means of an actuating mechanism in the panel which is operatively connected to the plurality of solar modules. The modules are arranged side by side in a rectangular matrix and the panel defines a form factor which may be sufficiently flat for installation within a glazed building envelope system. A closer scrutiny of the mechanical system of Dyson et al. reveals that their basic solution is unsuitable for use in mainstream building practices where requirements are uncompromising regarding cost, robustness, form factors and flexibility, and where simple and rapid installation by non-specialists is important. The mechanical solar tracking arrangements taught by Dyson et al. can be functionally described as xy arrays of modules suspended by tautly stretched cables or linked rod-like members within a rectangular frame. Various levers, belts, rods, etc at the periphery of the frame can be operated to cause differential motions of the cables or rod-like members suspending the modules, causing the latter to tilt and rotate. As a general rule, the angular precision requirements of modules containing solar concentrators
depend upon the concentration factor, and for moderate to high gain systems that appear relevant in the present context each module in the whole array must track uniformly with an error margin of a few degrees or less. Especially in cases where the panel shall be used in inclined or horizontal positions (e.g. skylights and roofs), this will be very difficult to achieve and shall at a very minimum imply very high tension forces in the suspension system, with corresponding stability requirements on the supporting frames and mechanical drive components. Even in the simplest case where the panel is vertical, it shall be laborious and demanding to set up a large array with the required precision and retain this precision during prolonged unattended operation, given the mechanical complexity of the system and its dependence on dimensional stability in long stretched or linked mechanical connections. Mechanical complexity and demanding mounting and maintenance procedures shall typically be cost-driving and incompatible with basic success criteria in the building industry, cf. above. A further problem relating to the mechanical arrangements taught by Dyson et al. is that despite the arguments put forward regarding use within glazed building envelopes, including windows, the disclosed systems shall encounter steeply increasing problems when the space between the envelope walls becomes smaller, i.e. when the panel thickness is reduced and the form factor becomes more flat: In this case, each module must be reduced in size in order to be accommodated in the more restricted space, the number of modules increases and the number of suspension wires or rods and associated drive linkages increases accordingly. At the same time, shorter distances between the suspension points on each module imply that higher precision is required on the mechanical alignment motion.
in order to maintain angular alignment precision. Finally, it may be pointed out that the systems taught by Dyson et al. do not lend themselves to incorporation onto irregularly shaped surfaces or into non-rectangular building envelopes. In US Pat. 7,187,490 M. Rabinowitz describes an ultra-flat tracking array based on an electronic film with a large number of embedded micro-mirrors that concentrate solar energy, cf. Fig.1h. The micro-mirrors are embedded in small spheres confined between two sheets and track the sun by rotating under the influence of individually induced dipoles. The mirrored micro-balls are covered with a thin spherical shell of lubricating liquid so that they are free to rotate in an almost frictionless encapsulation between the sheets. This concept requires individual control of thousands of microspheres and assumes the availability of printed transistors controlling each individual micro-ball, in addition to full row and column control circuitry. Such transistor circuitry does not exist at present, and most likely will not be available for low cost printing processes for several years to come. Furthermore, in most of the applications that appear relevant, the described local micro-ball control precision far exceeds what seems realistic to achieve with the technology being contemplated. A similar concept based on transparent spheres with a mirror mounted in an equatorial plane inside is described by O'Hara-Smith in US Pat. 6,227,673 B1. Here, the spheres are rotated by mechanical means: The spheres are squeezed between two flat sheets and rotate in parallel when the sheets are translated relative to each other. This concept relies on certain premises which are very difficult to meet in practice: The spheres must at all times maintain adequate friction at the contact points with the two sheets; even a momentary slippage for a given
sphere at one of the sheet surfaces shall cause irreversible loss of pointing direction and may bring spheres out of position with shifted spheres rubbing against each other. Furthermore, the light-transmitting surfaces (the sheet facing the incident light and the wall of the sphere) must be smooth and clear throughout the lifetime of the device, even when the spheres roll repeatedly across the surfaces. The task of combining unfailing friction with high optical clarity throughout an extended lifetime may have prevented this concept from attaining commercial viability.

In conclusion: There exists a particular need for novel methods and technologies that can provide a solar tracking system embedded in a flat package, which exhibits no mechanical motion outside the package, and which can be compactly integrated in a fixed position into walls, roofs, etc of buildings or in free-standing structures, with a low profile giving high resistance against wind and adverse weather conditions. While providing efficient capture of the insolation energy, the system should at the same time be cheap to build, install and operate, with low material consumption and reliable operation.

_Objects and advantages of the invention_

Accordingly, it is a major object of the present invention to provide easily scalable pointing arrays of multiple direction-critical elements for solar energy harvesting and other applications, where the elements are capable of rotation about one, two or three axes, and where the said arrays can be confined within a low profile and can be constructed at low cost while providing high precision and reliable operation.
It is another major object of the present invention to teach how multi-element pointing arrays according to the invention can be implemented in the harvesting of solar energy in the form of electrical power, light and heat. In particular, it is an object of the present invention to teach how multi-element pointing arrays according to the present invention can be integrated as low-profile energy-harvesting entities into structures such as building facades, roofs, walls, pillars, chimneys, etc., either surface-mounted or as basic constituents of the walls, roofs, etc.

It is a further major object of the present invention to teach how multi-element pointing arrays according to the present invention can be implemented as low-profile photovoltaic panels on or in the outer surfaces of vehicles, boats and other moving objects.

It is a further major object of the present invention to teach how multi-element pointing arrays according to the present invention can be implemented to reflect or project electromagnetic radiation, in particular light, in specific directions or onto specific targets, and how such implementations can contribute in, e.g. solar energy harvesting and remote illumination. An associated important object of the present invention is to show how relay optics in multi-element pointing arrays according to the present invention can provide new opportunities for solar energy sharing in cooperating optical networks on small and large scales.

Additional objects and advantages of the present invention will be set forth in the description that
follows, and in part will be obvious from the description, or may be learned by practice of the present invention.

Summary of the invention

The invention relates to a multi-element two- or three-axis pointing array comprising at least two direction-critical elements capable of receiving and/or transmitting and or reflecting electromagnetic or acoustic radiation and further comprising mechanical parts for motion control, wherein each element in the array is adapted to exhibit a pointing and/or alignment motion by rotating about two or three axes and align substantially in parallel with other elements in the array, wherein at least two of said elements are directly or indirectly operated by mechanical links to at least two physical structures that can translate and/or rotate relative to each other on at least one of said at least two physical structures, wherein said pointing array is adapted to be contained within a flat package, i.e. with all mechanical parts confined within a form factor where one dimension is substantially smaller than the others.

The invention may be implemented in a flat package which exhibits no mechanical motion outside its form factor, with applications in solar energy harvesting for the generation of electricity and/or for collecting and transmitting solar energy for heating and lighting applications. The flat package format enables compact integration in a fixed position in buildings to constitute parts of walls, roofs, etc or in free-standing structures. More generally the present invention may be implemented in multi-element pointing arrays for receiving and/or
emitting and/or reflecting electromagnetic or acoustic radiation.

**Mechanical**

Each element is mechanically linked to two or more separate driver bodies, i.e. physical structures that are each connected to a mechanical power source and transmit the motor forces that move the pointing array. The driver bodies follow different motion patterns that can be precisely controlled in a predictable manner by means of various types of mechanical guiding and restraining elements well known in mechanics which may include e.g. pivots, hinges, slide-guides, levers and rollers. Via their mechanical links to at least two driver bodies that move differently, the elements are brought to change their pointing direction in space in a precise and predictable manner. By appropriate selection of driver body geometries, mechanical links, guides and restraints, simple geometrical arrangements can be implemented that make a plurality of elements move simultaneously and in precisely defined pointing directions, either parallel to each other or in a preselected differential pattern. The driver bodies are structures where all constituent parts have a fixed spatial relationship to each other, so that the linking attachments of each driver body to the elements move as if attached to a monolithic body. At least one of the driver bodies extends across essentially the whole array, providing a high degree of robustness and precision, and allowing considerable freedom regarding the shape of the array, which may be rectangular, round or of a more complex contour.

The elements may be linked at a pivot point, to each of at least two of the physical structures. The physical
structures may typically remain essentially parallel during the pointing motion. To minimize differential rotational motion between the at least two of the physical structures, the structures may be subjected to mechanical restraints which may comprise torsion bars and/or hinges. The mechanical restraints may also comprise sets of linear sliding guides restrained to move in orthogonal directions and where the linear sliding guides may comprise slits and/or swallow-tail guides and/or linear roller bearings.

The physical structures may be in the form of, e.g. a flat or corrugated solid plate, and/or a honeycomb structure, and/or a mesh, and/or a truss structure, and/or a frame with stretched wires or attachment positions around a periphery.

The direction-critical elements may be linked at a pivot point in a first of the at least two physical structures and via a mechanical connection at another point in a second of the physical structures. The pivot points may be defined by a ball joint or a rod penetrating through a hole with elastic lining or an elastic membrane surrounding the hole, or a hinge connection.

Using guiding tracks or slots

The elements may have a first sliding and/or rolling pivot point linkage at a localized position on a first of the physical structures, and comprise a rigidly attached rod-like part which passes through a guiding track or slot on a second of the physical structures and a guiding track or slot on a third of the physical structures, the guiding tracks or slots on the second and third of the physical structures always maintaining a geometric relationship
such that the spatial orientation of the rod-like part is uniquely defined. The physical structures may translate in two mutually non-parallel directions and an additional structure may execute a rotating motion.

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*Tilting superimposed on rotation.*

The elements may be mounted on a first physical structure which can rotate about a first axis, and where this first physical structure carries two or more array elements that can rotate about axes that are not parallel to said first axis and preferably substantially normal to same. Said array elements may be mechanically connected to a second physical structure which is attached to said first physical structure, where said second physical structure can execute a translatory and/or rotating motion relative to said first physical structure, said translatory and/or rotating motion acting via mechanical linkages upon said array elements and causing them to rotate in synchronism.

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*Spheres between sheets*

The physical structures may be in the form of sheet-like objects which are kept apart by a plurality of spacer objects confined between the sheet-like objects, where each spacer object presents a spherical or cylindrical surface at the contact points against sheet-like objects and can roll when the sheet-like objects are translated parallel to each other. The spacer objects may be spheres or part of spheres that incorporate direction-critical elements within or on the spacer object itself, on rigidly attached protrusions, pins or rods, or on flexible and/or elastic material attached to the sphere wall. Each direction-critical element is mechanically restrained so as to maintain a fixed position on at least one of the
sheet-like objects. The spacer objects may roll against a smooth surface on one of the sheet-like structures and roll in the confinement of a hole or pit on the other of the sheet-like structures. Parts of the spacer objects may be optically transparent. The sheet-like objects may be kept together by magnetic, electrostatic, elastic or pneumatic forces distributed across their surfaces.

Tilted and multiple arrays

The multi-element array may be adapted to be mounted in a mechanical structure which can tilt and/or translate the array itself. The array may be powered via one or more translating and/or rotating mechanical linkages to one or more mechanical power sources and share the power sources with one or more other arrays, and the array may transmit mechanical power to other arrays via one or more mechanical linkages integrated into the array. Further, the array may be adapted to be arranged along a linear mechanical power shaft that translates and/or rotates, or near the points in a two-dimensional matrix where two sets of mechanical power shafts cross each other, and to pick up mechanical power from the mechanical power shafts in one of the following ways: By permanent hook-up of all elements, or by engaging/disengaging a connection for one array or a subgroup of arrays in the matrix at a time.

Tracking an object

The direction-critical elements may track the sun or another physical or virtual object, for example based on directional tracking input obtained from one or more radiation detectors in conjunction with logic circuitry, where the detectors intercept electromagnetic or acoustic radiation emitted or scattered from the object and determine its direction of incidence towards the
direction-critical elements. The detectors may be of the quadrant- or other direction-sensitive type and they may be located in at least one of the direction-critical elements.

Alternatively tracking may be achieved by means of logic circuitry, position encoders and servo hardware, the logic circuitry deriving trajectory and timing information from a stored program, the program being either pre-loaded or generated in the logic circuitry by a learning algorithm.

The array may further comprise on-board logic and/or memory and/or electrical power storage facilities and the direction-critical elements may comprise photovoltaic elements.

Directing light

The elements may comprise an optical structure for controlling and directing light which may comprise refractive and/or reflective and/or holographic and/or diffractive and/or absorptive and/or fluorescent and/or spectrally selective optical components. More precisely the optical components may comprise spherical simple or compound lenses, transparent monolithic objects in the form of spheres and/or light guides, holographic lenses, mirrors, Fresnel optics, edge- or bandpass- or greytone optical filters, optical modulators, polarizers.

The optical elements may reflect incoming light onto a target at some distance from the array, and wherein the target is provided with means to generate feedback information on the amount of light that strikes the target, and wherein the feedback information is
transferred to a processor which controls the motion of the direction critical elements. The target may be a mirroring device that relays solar power onto yet another target, or it may be a solar energy collector with one or more of the following capabilities: Generation of electricity, conversion to thermal energy, simultaneous or sequential relaying of light energy in a linear or branched optical relay chain. The means to generate feedback information may comprise photodetectors or temperature sensors, and the feedback information may be transferred from the target to the processor via a wired or wireless link or an optical fiber.

The optical structure may contain a light source such as incandescent and/or light emitting diode and/or laser and/or fluorescent and/or light guide, and light emitted from the light source may be collected by an optical system within the element and projected as a light beam from the element in the multi-element pointing array. The light beam from the element may be collimated and parallel to the light beam from at least one other element. The multi-element pointing array may constitute a directive searchlight or illuminator.

The light intensity and/or colour from the light sources in the elements may be independently controlled. Concentrating energy collector

The multi-element pointing array may be an acoustic or electromagnetic energy collector where radiation incident upon the multi-element pointing array is concentrated by radiation concentrator structures in at least two of the direction-critical elements and brought
to impinge on materials and/or structures which capture at least some of the radiant energy incident upon them.

The radiation concentrator elements may comprise of one or more lenses and/or mirrors which concentrate electromagnetic radiation in the form of a focal point, focal line or extended spot.

The materials and structures may convert incident radiative energy into electrical power. The materials and structures may comprise a light trapping cavity, the light trapping cavity having an entrance opening for admitting light, one or more photovoltaic elements, and cavity walls that are highly reflecting where not covered by the photovoltaic elements. A light trapping cavity may have a light reflection geometry wherein light is reflected from internal surfaces in a predefined sequence, and the light trapping cavity may have a geometry wherein an incident light beam reflects at different incidence angles and/or polarization conditions when undergoing multiple reflections within the cavity. Further the light trapping cavity may contain photovoltaic elements with different and complementary optical absorption characteristics.

The antenna or detector materials and structures may convert incident radiative energy into thermal energy. The array may be encased in a closed volume suffused by a gaseous coolant which is guided by a pressure gradient past or through the antenna or detector materials and structures.

The materials and structures may form electromagnetic guide- or relay elements which can transmit electromagnetic power to points outside the concentrator.
elements and these elements may comprise an optical fiber or microwave waveguide. The points outside the concentrator elements may be located in illumination structures, or these points may be located in structures which convert incoming radiation to electrical or thermal energy.

**Brief description of the drawings**

Figs. 1a-h show some examples of prior art pointing element configurations, with emphasis on solar energy harvesting.

Figs. 2a,b,c illustrate the basic principle of collinear motion of multiple elements that are linked to two parallel planes moving independently. Each element is represented by a pin that penetrates both planes.

Figs. 3a,b,c show a preferred embodiment of the present invention where directional control of multiple elements is achieved by two planes moving on two sets of hinges rotating about mutually orthogonal axes. In Figs. 3a, 3b only the mounting pins linked to the two planes are shown, whereas 3c shows an example where optical concentrating elements with Fresnel lenses are mounted on top of the pins.

Figs. 4a,b,c, show top views of arrays of differently shaped or arranged elements that are in non-tilted position.

Fig. 5 shows an embodiment of the present invention where directional control of multiple elements, represented by pin-mounted conical structures, is achieved by the relative motion between two planes linked by hinged torsion bars.
Fig. 6 shows an embodiment of the present invention where directional control of multiple elements, represented by pins, is achieved by the relative motion between two planes moving in mutually orthogonal, linear guides.

Figs. 7 a,b,c,d,e show alternative embodiments of the present invention.

Figs. 8 a,b,c show how angular tracking can be achieved by a set of linear and/or curved guides linked to rotating and/or translating structures.

Figs. 9 a,b shows the basic configuration for two-axis angular tracking by means of a rotating platform and a hinged tilting element, along with a definition of relevant angular coordinates.

Figs. 10a,b,c show further definitions of certain mechanical parameters related to the rotating platform and tilting element configuration, and illustrate how a large panel can be divided into a series of low profile slats.

Fig. 11 shows how circular alignment platforms can be packed into hexagon modules, retaining a hexagonal close-packed pattern when the modules are assembled in an area-covering mode.

Fig. 12 shows an example of the present invention where the rotating base platform is an open frame in the form of an annulus, and where panels are linked mechanically to execute a tilting motion in parallel.

Fig. 13 shows a variant of the annulus design where the
mechanical linkage between panels is achieved by means of a curved bar.

Figs.14 a,b show an embodiment of the present invention where the annulus design is implemented with concentrating optics in the tilting panels.

Figs.15 a,b show an open frame equivalent to the annulus design.

Fig. 16 shows an embodiment employing the scheme of Fig. 15 with concentrating optics in the tilting panels.

Figs. 17 a,b,c illustrate a principle where a pre-tilt is used in conjunction with tilting panels to reduce shadowing effects.

Figs.18 a,b,c show an embodiment of the present invention where a pellicle is used as a deformable mirror.

Fig. 19 is a view of the cross-section of an embodiment of the present invention, with lens and tracking mechanism, photovoltaic chip and conductor sheet with electronics attached to it.

Figs.20 a,b,c,d,e,f,g,h show different types of concentrating optics that can be used in certain embodiments of the present invention.

Figs. 21a,b,c show versions of the present invention as applied in photovoltaic solar power conversion.

Fig.22 shows a non-concentrating array of photovoltaic cells that are aligned such that they face the sun and
track it throughout the day.

Fig. 23 shows an application of the present invention where a tracking array of optical concentrator elements converts solar radiation to thermal energy.

Fig. 24 is a view of an embodiment where the incoming light is transported via a fiber to an outside photovoltaic device or other type of device.

Fig. 25 shows an application of the present invention for transmitting and distributing light.

Fig. 26 is a view of an embodiment where a fan is transporting heat away from photovoltaic material.

Fig. 27 shows tracking solar arrays according to the present invention that are integrated into the walls and roof of a house.

Figs. 28a,b show tracking solar arrays according to the present invention that are integrated into the outer surfaces of a car and a boat.

Fig. 29 shows an example of a light trapping configuration.

Fig. 30 is shows the principle of a tandem solar cell.

Figs. 31a,b are examples of light trapping structures incorporating tandem solar cells.

Fig. 32 shows a thin-film solar cell.

Fig. 33 illustrates reflection of light from a metal mirror.
coated with a thin film material.

Fig. 34 is an example of a light trapping cell with skew angled walls.

Fig. 35a shows an array of tiltable mirrors relaying an incoming parallel bundle of light beams as another parallel bundle of light beams onto a target.

Fig. 35b shows multiple arrays of tiltable mirrors relaying incoming parallel light beams onto a common target which contains a retroreflecting device.

Fig. 36 shows multiple arrays of tiltable mirrors relaying incoming parallel light beams onto a common target.

Fig. 37 shows an array of tiltable mirrors mounted on rotating spheres.

Figs. 38a, b show arrays of tiltable mirrors based on rotating spheres that carry mirrors on external facets or within.

Fig. 39 shows an example of a free-space solar illumination relay arrangement inside a house.

Fig. 40 shows part of a light-emitting pointing array.

Fig. 41 shows an arrangement where a plurality of individual pointing array panels is controlled by a matrix of mechanical power trains driven by two motors.

Figs. 42, 43, 44 show different aspects of a rotate-and-tilt panel, which may be coupled to other panels as
exemplified in Fig. 42.

Fig. 45 shows another variant of a rotate-and-tilt panel.

The reference numbers relate to the individual figures, a fact that is also reflected in the detailed description below. This implies that the same object may be referred to by different numbers in different parts of the text.

**Detailed description**

The direction and position of a straight line in three-dimensional space can be defined by the three-dimensional coordinates of at least two points at separate positions on the line. Thus, taking two points on an object to define the attitude or pointing direction of the object, the pointing direction can be controlled by attaching each of said two points to separate driver bodies and moving those separate driver bodies relative to each other. The direction and position of a straight line in three-dimensional space can also be defined by the three-dimensional coordinates of one point on the line and the direction vector of the line from that point. This direction vector may be uniquely determined by its intersection with one-dimensional features on two or more surfaces in space. If these surfaces move relative to said point on the line, the direction vector changes.

In the present invention, multiple objects are mechanically connected between two or more driver bodies or sets of driver bodies, causing all connected objects to move in a predefined manner. In most cases of practical interest, the driver bodies shall be attached at points lying on concentric spherical shells or on mutually
parallel planes. The latter shall be the object of primary but not exclusive focus in the following.

Mechanical

The basic principle is illustrated in **Fig. 2**, where a mechanical arrangement based on translational displacements between two parallel but separated planar sheets makes it possible to control the pointing direction of large numbers of objects that are anchored at one point in each sheet. If the objects are anchored such that their pointing axes are initially collinear, their pointing directions will change but remain collinear. This shall now be described in some detail with particular reference to **Figures 2 - 7**, for the case where the sheets are translated relative to each other without relative rotation about their surface normals. Examples of alternative embodiments based in part on rotational motion and more than two physical driver bodies are described with reference to **Figs. 8a, b, c**.

**Figs. 2a, b, c** illustrate the case where the objects are three straight pins that penetrate both sheets in tightly fitting holes. The pins are initially oriented at right angles to the sheets as shown in **Fig. 2a**, and the sheets are initially separated by a distance Z₁ along the z axis. By moving the top sheet parallel to itself (i.e. without rotation about the z axis) in the y direction while maintaining the bottom sheet in its original position as shown in **Fig. 2b**, all pins are tilted in the yz plane by the same amount as shown. The pins can tilt in the holes in each sheet at their penetration points and may or may not be allowed to slide lengthwise through the holes, depending on the application:
If the pins are restrained from sliding in the holes of both the upper and lower sheets, the length of each pin between the sheets is constant and a hinged motion results where the sheets come closer together (separation distance \( Z < Z_1 \)) as the upper sheet is moved from the initial position. If the pins are allowed to slide in the holes of one or both the upper and lower sheets, the length of each pin between the sheets shall vary, depending on how the distance \( Z \) between the sheets varies during the motion of the upper sheet. Thus, if \( Z \) is constant during a translation \( Y \) of the upper sheet, the pin length between the sheets would increase from \( Z \) initially to \( \sqrt{Z^2 + Y^2} \). This is the case if, e.g. the sheet motion is confined to a linear guide parallel to the \( y \) axis.

In Fig.2c, the top sheet has remained stationary, while the bottom sheet has been moved in the \( x \) direction from its initial position in Fig.2a. The bottom sheet has been moved parallel to itself (i.e. without rotation about the \( z \) axis). All pins are tilted by the same amount, but now they tilt in the \( xz \) plane.

From the above, it follows that by a combination of \( x \)-motion of the lower sheet and \( y \)-motion of the upper sheet (or vice versa), the pins can be brought to tilt in any desired direction.

It is clear that numerous alternative embodiments are possible, based on the same fundamental principles as described above. Thus, instead of a snugly fitting hole around a portion of a pin, a rotating ball joint shall be included in descriptions below. Also, changes in length between anchoring points in the upper and lower sheets during motion of the sheets may be absorbed by other means.
than sliding axially through a hole, examples are
telescoping rods and elastic stress members.

It is important to note that collinearity of all pins
during the motion is lost if either of the sheets is
allowed to rotate about its surface normal during the
motion. There are several mechanical arrangements that can
take care of this problem:

In Fig.3a is shown how the top and bottom sheets are
both supported by hinges that are anchored to a common
plane base. As is highlighted in Fig.3b, one set of
hinges, supporting the top plane, is oriented in one
direction, while another set of hinges, supporting the
bottom plane, is oriented at right angles to the first set
of hinges. The two planes can move independent of each
other by tilting the hinged sidewalls, causing the set of
pins to point in any desired direction within the free
range of motion. This is illustrated in Fig.3c, where a
set of Fresnel-lens based optical concentrating elements
on pins are shown in tilted position. The length of pin
connecting the penetration points in the upper and lower
sheets shall depend on the relative positions between the
upper and lower sheets, and allowance must be made for a
sliding motion of the pin through one or both of the
penetration points. Also, the slewing response of the pins
to a given motion of the upper or lower sheet depends
strongly on the relative positions of the upper and lower
sheets. This does not represent a problem when, e.g. a
feedback system or a look-up table in conjunction with
position information is used.

In many applications, e.g. involving antennas or
solar energy converters, it is desired that the tiltable
elements in an array shall be close together and provide dense area coverage. In the example shown in Fig. 3c, the front end of each element is circular, and the elements are positioned relative to each other in a hexagonal close packed (HCP) pattern. This shall be the preferred arrangement in many applications, since it provides large freedom of motion in all tilting directions and yields the highest possible surface covering density for circular objects of equal size packed side-by-side. However, the present invention provides great freedom in accommodating different types of area-covering array elements in a wide range of different patterns. Some examples are given in Figs. 4a-c, which show top views of arrays of differently shaped elements that are in non-tilted position: As can be seen from Fig. 4a, a square array of close-packed square elements provides complete area coverage with no cracks or glitches between neighbouring elements. In practice, a certain distance must be allowed between elements to account for finite mechanical tolerances. Clearly, the elements must not be allowed to execute uncontrolled rotation about their tilting axes. This can be handled by incorporating mechanical restraints against rotation in the tilting mechanisms according to the present invention, but generally is a complicating factor. Furthermore, the maximum possible tilt angle above a planar support is less in the direction of the corners of the elements. This can also be handled by employing a support structure with openings that the corners of the elements can dip into. Fig. 4b shows a HCP arrangement of circular elements as discussed previously. Even at maximum density as shown here, the areal coverage is limited to approximately 0.91, and finite mechanical tolerances shall in practice reduce the areal coverage further. One way to increase the areal coverage is illustrated in Fig. 4c: Here, the circular
elements are arranged in two tiers: In the lower tier are elements in a HCP pattern as was shown in Fig.4b, but with some of the elements removed. In the openings thus created are mounted somewhat larger elements that form an upper tier in an expanded hexagonal pattern. Another way of increasing the area coverage over that shown in Fig.4b is to fill the openings with a set of smaller objects (not shown). The latter need not be in a plane raised above that of the objects in the HCP pattern and may be linked to the same angular tilting control as the larger elements.

In Fig.5 is shown how a hinged motion in two orthogonal directions can be achieved by means of one or more torsion bars (1) that are anchored by a hinge (2) to a flat lower sheet (3) and run through a hinge (4) on the upper sheet (5). Directional antenna elements in the form of open cones (6) are rigidly mounted on mounting pins (7) that pivot about rotational joints (8), (9) in the upper and lower sheets, respectively. The pivot points (8) and hinge axes (4) on the upper sheet lie in a common plane, as do the pivot points (9) and hinge axes (2) in the lower sheet. Each torsion bar has four torque-transmitting hinges (10). Two motors (11), (12) are shown linked to the upper sheet, providing position control and displacement force in two orthogonal directions. The hinge positions, etc., can be varied without departing from the basic principle shown, e.g. by making the torsion bars as complete loops or having a gap at the upper sheet instead of the lower sheet. The two sheets are kept apart by a set of springs (13) surrounding the pins, but many other arrangements are obvious to the skilled person. Also, ball joints are shown at the pivot points where the pin passes through the upper and lower sheets. A ball joint is advantageous in many instances where precision and load
bearing capacity are of importance. A feature of the architecture shown in Fig.5 is that motion takes place without changing the distance between the upper and lower pivot points. Thus the connecting pins do not need to absorb any shortening or lengthening by telescoping or sliding. Furthermore, the upper and lower sheets are restrained by the torsion bars from rotating about their surface normals, which is required for all pins and elements to execute the same rotational motion about their pivot points.

In Fig.6 is shown an arrangement where both the upper and lower sheets run through guides, the upper guide allowing translation without rotation in one direction, the lower guide allowing translation without rotation in a direction orthogonal to the first.

Figs. 7a,b,c show examples of alternative embodiments of the present invention: In all cases, there is an upper and a lower sheet which can translate relative to each other while being kept at a constant distance from each other. Not shown, but present in each case, are guides or other arrangements which confine the motion of each sheet to be purely translational, i.e. no rotation about a surface normal axis is allowed. In Fig.7a, the upper sheet has openings which hold spheres in place, while allowing them to roll on the lower sheet when a translation of the sheets occurs. The spheres roll smoothly in the holes, but exhibit friction against the surface on the lower sheet. A mild force draws the two sheets together. This can be achieved by, e.g., elastic pressure from above and below the sheets, or by the upper sheet and lower sheet being magnetized as indicated symbolically by the arrows in Fig.7a. As the sheets are translated, the pins extending
from the top of the spheres will be rotated in such a manner that an initial collinearity is maintained. In Figs. 7b,c are shown a set of pins that penetrate an upper and a lower sheet which can slide against each other, either supported by roller bearings as in Fig.7b or by direct surface-to-surface contact as shown in Fig.7c. The pins rotate about penetration points in the upper and lower sheets where elastic insets in the sheets permit a certain motion. As shown in the inset, the pins are kept from axial displacement relative to the upper sheet by a narrow neck at the upper penetration point, whereas they can slide axially through the penetration point in the lower sheet during pointing alignment.

Fig. 7d shows a variant related to the one shown in Fig.7a: The top plate (8) and the bottom plate (9) are kept at a fixed vertical distance from each other. In this particular example this is achieved by using spheres (12) that roll against the bottom plate (9), but which are kept in position relative to the top plate (8) by penetrating the same top plate through holes (6) with a diameter which is smaller than that of the spheres (12). The rod (7) follows the x - y motions of the bottom plate (9), and by doing so rotates the sphere (4) in the shaped hole (11) in the top plate, and hence the trough (2) and the directional element (1). The rod (7) is fixed onto a sphere (3) which is free to rotate in a shaped hole (10) in the bottom plate. The rod (7) can slide smoothly in and out along a bore channel in the hollow tip extension (5) when the top and bottom plates move relative to each other in the x - y directions. The two plates (8) and (9) are drawn together by a force which at the same time permits the plates to move laterally relative to each other. The corresponding arrangement is not shown in Fig.7d, but can
be designed in several possible ways, e.g. incorporating elastic components as in Fig. 5 or magnetic forces as in Fig. 7a.

**Fig. 7e** shows a variant of the arrangement in Fig. 7d: Here, the rod (5) is fixed on the upper sphere (4) and extends all the way down through a bore channel in the lower sphere (3) where it can slide smoothly when the top and bottom plates move relative to each other. As before, the spheres (4) and (5) can rotate in the shaped holes (11) and (10), respectively, and the tilt direction of the through (2) with the directional element (1) changes accordingly.

According to the present invention, the elements in a multi-element pointing array may also be directly or indirectly linked to more than two physical structures that can translate and/or rotate relative to each other. This is illustrated in Figs. 8a, b, c: In these cases, a set of tiltable pins (1) is anchored at fixed pivot points in a planar sheet (2). The tilt direction of each pin is defined by the crossing point of guides located in two separate sheets (4), (6), as observed from the pivot point. This crossing point moves when the different guides move due to rotational and/or translational motion of the physical structure carrying the guides. As long as the guides are not near-parallel, adequate control of the pins can be achieved.

In **Fig. 8a** five pins (1) penetrate a stationary upper sheet (2) and a set of spiral guides (3) in a stationary lower sheet (4) which is parallel to the upper one. Each pin is allocated its own spiral guide which is located above a carousel (5) on a stationary lowest sheet (6)
which is parallel to sheets (2) and (4). The carousel can rotate about an axis which is perpendicular to the sheets and passes through the spiral center, and has a linear guide which the pin passes through. Since each spiral guide can be completely traversed by rotation of the carousel underneath, the corresponding pin can be brought to point in any direction (θ,φ) defined by the penetration point in the top sheet and any point on the spiral. Thus, by parallel rotation of all carousel guides, all pins can be aligned collinearly in any direction within the defined range of angles (θ,φ). Alternatively, each carousel can be activated separately from the others, enabling each pin to point in a direction which may differ from the directions of the other pins. Whereas only rotational motion and no translational motion is employed in this case, more complex variants of this scheme are possible: In one class of embodiments, the sheet (2) is brought to translate relative to sheets (4), (6) while the carousels rotate at the same time, in which case the tilting motion engendered by the rotating carousels is superimposed on the tilting motion caused by translation of the sheets. A special case of the latter is where the pins penetrate the carousels at a fixed radius and sheets (2) and (6) translate relative to each other, with sheet (4) removed. Such a combined motion can cause the tilting vectors of the pins to execute a set of epicycles. This could be of potential use in certain scanning and searching applications of the present invention.

Fig.8b shows another variant where three planar structures are involved, two of which contain linear guides: Five pins (1) penetrate a stationary upper sheet (2), a set of linear guides (3) in a lower sheet (4) which can translate in a direction perpendicular to the guides,
and a set of linear guides (5) in a lowest sheet (6). The guides (3) and (5) are perpendicular to each other, and the sheet (6) can translate in a direction normal to the guides (5). As can be seen from Fig. 8b, all 5 pins tilt in parallel when the sheets (4) and/or (6) are translated.

The basic principle of differential motion (rotation and/or translation) of structures containing mechanical guides, as exemplified in Figs. 8a, b, can be employed in a wide range of embodiments, some of which can generate highly complex but precisely controlled motion patterns in an array of tiltable elements. An example is shown in Fig. 8c, where the arrangement is very similar to that shown in Fig. 8b, with pins (1), upper sheet (2) and linear guides (3) in the lower sheet (4). Here, however, the guides (5) in the lowest sheet (6) are along curves that cause the pins to wiggle in the x direction in response to linear translation of sheet (3) in the y direction. This wiggle is superimposed on any tilt in the x direction caused by a motion of sheet (6) in the x direction. As shall be evident to the skilled person, further variants are possible where the sheets (2), (4) and (6) need not be parallel or planar.

Figs. 9a and 9b show how two-axis alignment of a given planar object (1) with a surface normal N can be achieved by a combination of a rotation of a platform (2) (rotation coordinate φ about z axis, which is a surface normal to the platform), combined with a tilt relative to the platform (polar angle θ). This principle, in one version or another, is routinely used in a large number of mounts for antennas, floodlights, etc, and also for aligning solar panels against the sun. In order to be able to point the surface normal N in any direction in space,
the mechanical arrangement must allow the polar angle $\theta$ to range from 0 to 180 degrees and the azimuth angle from 0 to 360 degrees, cf. Fig.9a. In many instances, hemispherical coverage is adequate, corresponding to a range of polar angles between 0 and 90 degrees. This shall be the case in the arrangement shown in Fig.9b, where a circular disc carries the planar object (1) that is to be tilted.

As can be seen from Fig.10 a, the maximum height $h$ of the planar object above the platform is:

$$h = s \cdot \sin\theta$$

where $s$ is the side dimension of the planar object and $\theta$ is the tilt angle. Clearly, in cases where planar object (and thus $s$) is large, the maximum height $h$ shall also become large as the tilt angle increases. This is often undesirable, and may be disqualifying in certain applications, e.g. in solar energy conversion where practical aspects relating to limited available space, manoeuvrability and susceptibility to wind loads can be critical. As is illustrated in Figs.10 ab, c, the maximum height $h$ can be reduced while at the same time conserving the area of tilted surface, by dividing the original tilting object shown as (1) in Fig.10 a into a plurality of smaller objects, e.g. like the Venetian blind-like arrangement of rectangular panels shown (3a)-(3e) in Fig.10 b.

The platform may have any shape and needs not be planar or even sheet-like, but a circular platform is a good choice in many practical applications where space is limited and full freedom of azimuth motion (360 degrees) is required. In order to obtain maximum coverage of such a platform with a number of panels or slats of limited
height, it is possible to shape each panel to conform with the circular outer perimeter. This is shown in Fig.10 c. A number of circular platforms may be positioned to cover a given surface, in which case the maximum surface coverage is achieved by the well-known close-packed hexagonal (HCP) arrangement shown in Fig.11. As can be seen further from Fig.11, each platform can be incorporated into a module with hexagon sides without sacrificing the areal surface covering density of the circular platforms. The modules can be added one at a time in all directions, to create a dense wall or roof cover. The “dead space” at the corners inside each hexagon can be used to position mechanical and electrical equipment to achieve controlled motion of the platform and its internal mechanics.

The platform needs not be massive, and in many cases distinct advantages are achieved by open frame solutions. Fig.12 shows an example where the platform is an annular frame (2) where the tilting panels on the form of rectangular slats (3a)-(3c) can rotate about hinges (1) in the rim of the annulus. The slats are mechanically locked to rotate in parallel by means of a common yoke (6) rotatably connected to the top of the slats by joints (7). The tilting motion is controlled by a motor (5) connected to one of the slats at its rotational axis. At the same time, the annular frame itself can be rotated by means of a second motor (4) which drives a cylinder (8) which is pressed against the outer rim of the annular platform. By employing open frame solutions, the amount of material and resulting weight of the platform is reduced compared to the massive version, and certain technical solutions become possible. For example, advantages are achieved by complex tilting objects being able to dip down into the void inside and below the open frame platform, cf.
detailed descriptions below.

As shall be evident to the skilled person, the example in **Fig.12** shows only one amongst a large number of embodiments that can be based on this general idea. Thus, the mechanical linkage between the slats can take the form shown in **Fig.13**, where the top of the slats (3a)-(3c) are hinged into a common curved rail (9) which has a shape corresponding to a part of the platform annulus (2) below. This avoids shadowing of incoming radiation on the slats. Likewise, the arrangement for fastening the slats onto the platform, mounting and rotating the platform, linking the slats, etc can be varied numerous ways without departing from the basic concepts of the present invention.

When the structure in **Fig.13** is used as a pointing mirror array, each panel (3a)-(3c) is a planar mirror, and there is strictly no need for the platform to be open in the middle. In other applications, however, the panels contain optical elements that concentrate incoming light to a focus down below, and where the open frame design is very useful to create a simple and compact device. An example of this is shown in **Figs.14 a,b**, where each panel (3a)-(3c) contains two or more Fresnel lenses (10) (clearly, equivalent embodiments are possible where individual lenses, which may be of any kind, are controlled by the same principles as shown in **Figs.14a,b**). The light is focused behind the lenses and strikes a photovoltaic cell (11) positioned on a structure linked to the panel in front of it. In the perspective drawing **Fig.14 a** and the side view drawing **Fig.14 b** the structure is shown as a bar (12) which is parallel to the panel in front of it and connected to the latter by struts (13). A connecting bar (14) links the system such that the panels
tilt simultaneously and in parallel. As shown, the Fresnel lenses are positioned as discrete, identical elements side by side along each panel, forming a point focus behind them. To maximize the surface coverage, each panel could be shaped as indicated in Fig. 10 c, and the Fresnel lens pattern could extend all the way to the edge of each panel. Also, it is possible to use optics that creates a line focus instead, parallel to and extending along the bar (11).

Another variant of the basic rotate-and-tilt principle in combination with multiple mechanically linked panels is shown in Figs. 15 a,b: In the example shown here, incident light (6) illuminates a set of panels (1a)-(lc) that are rigidly mounted on straight members (2a)-(2c) linked to two open frames (3), (4). When the frames are translated relative to each other as shown by arrows (5), a hinged motion results and all panels are tilted by the same angle. The lower frame is mounted so as to provide a rotational degree of freedom in the azimuth (7) (details not shown). An extension of the structure in Figs. 15 a,b with receiver elements analogous to those discussed in conjunction with Figs. 14 a,b is shown in Fig16.

As can be understood by inspection of Figs. 15 a,b, the panels shall partially shadow each other when they are in tilted position (cf. Fig. 15 b) to face radiation (shown by arrows) that is incident at an oblique angle, unless they are spaced apart to a considerable extent. However, spacing them apart shall reduce the areal coverage of the device in non-tilted position (cf. Fig. 15 a). Figs. 17 a,b,c illustrate how this problem can be mitigated by a minor modification implying a fixed pre-
tilt of the panels (1) relative to the straight members (2) that support them. In Fig. 17 a, the panels are mounted at right angles to the members as shown previously, with panel-to-panel distance chosen to give 100% areal coverage for light coming from directly overhead. As can be seen in Fig. 17 a, all panels except one lose half of the radiation when tilted towards incoming light at the angle shown, due to shadowing. By pre-tilting the panels as shown in Figs. 17 b, c it becomes possible to retain 100% areal coverage for radiation incident directly from above, while at the same time reducing the shadow effect when the radiation is incident at an oblique angle.

Yet another variant of the basic rotate-and-tilt principle, exemplified in combination with multiple mechanically linked panels is illustrated in Figs. 42-45: Here, the panels are shown as planar direction sensitive elements (1) with rectangular outline which are arrayed in rows where all elements in a given row have their surface normals or optical axes pointing in an essentially parallel manner and remain in parallel as they execute an angular tracking motion. The elements may be in the form of e.g. mirrors, lenses, solar panels or antennas and are shown in a planar form here, but may more generally be shaped as thick lenses, parabolic mirrors, etc. In this variant of the basic rotate-and-tilt principle, the panels with the arrayed elements can be designed to provide a higher degree of area coverage than the azimuth-rotating carousels illustrated in Fig. 11 since "dead area" between the moving platforms can be greatly minimized: As shown in Figs 42-44, the elements (1) are mounted in a rectangular frame (2) that can rotate about an axle (3) aligned in the y-direction (cf. Cartesian coordinate system inset
referred to frame in Figs. 42 and 44. Several types of mechanical arrangements are possible to achieve this rotational motion, cf. below. Each element can further rotate about the x-direction relative to the frame, between the hinged end-points (4), (5) shown in Figs. 43, 44 or about an axle (13) as shown in Fig. 45. The end-points (4), (5) are connected to frame-mounted linear activator members (6), (7) which can execute a relative motion (8) along the y-axis. In Figs. 43, 44 the first activator member (7) is a fixed part of the frame itself, whereas the second activator member (6) is a rod which has been omitted in Fig. 42 for clarity. As can be seen, this type of arrangement can cause all elements in a given frame to rotate in unison about two axes.

With the mechanical arrangement shown in Figs. 43, 44, the surface normal N can at most be rotated by 90 degrees about the frame-fixed Cartesian coordinate system, providing only half hemispherical angular coverage. As shall be evident to the person skilled in the art, however, many types of mechanical modifications to the arrangement shown are possible that allow the elements (1) and second activator member (6) to dip into an opening in the frame (2) and thus make it possible for the surface normal to have 180 degrees of rotational freedom about the x-axis. Alternatively, each element may be mounted on and rotate about a frame-mounted axle (13) which is rotated by a common link to an activator means. One example is shown schematically in Fig. 45, where axle supports, etc have been omitted for clarity: The axle (13) is terminated by a cylinder (9) in contact with a frame-mounted linear activator member (10). When the activator member is moved (11), the elements rotate in unison and can execute complete hemispherical pointing motion by a combined
motion of the linear activator (10) and rotation (12) by the axle (3).

In addition to allowing the construction of very low profile embodiments, the present variant of the basic rotate-and-tilt principle makes it possible to achieve a very high degree of area coverage, by tiling multiple frames together and coupling them in a common mechanical drive system to make them track in parallel. Thus, a large number of area-filling frames may be controlled by very few mechanical drive motors, and in certain cases only one motor is required for controlling each of the two independent tilt motions in the whole array. In Fig.42 three frames are shown side by side. In this example, the axle of each frame is terminated in a roller which is mechanically in contact with a linear activator member (13). When the latter moves (14) all frames rotate in unison. This type of mechanical activator linkage can be extended to encompass a considerable number of frames, also in a two-dimensional arrangement. Depending on operational conditions, precision requirements, etc the friction-based roller may be substituted by a chain- and sprocket combination, toothed linear linkage member or other means well-known in the art.

Instead of mechanically solid panels that are rotated on the base platform, it is possible to use the same basic principle where a set of parallel mirror surfaces are tilted relative to the platform, but where each mirror surface is created by a pellicle, i.e. a reflecting (e.g. metallized) thin film which is stretched flat. An example of this is shown in Figs.18 a-c, where three different tilt angles are exhibited in a side view. The film (1) is stretched taut at all times in the lateral direction, and
has a metallized mirror-like surface. A set of thin rods or wires (2) and knife edges (3) run parallel to each other, where the knife edges can be shifted in the vertical direction by a common mechanical member (4). In Fig.18a the knife edges are fully lowered, and the film is flat. Figs.18b,c show the knife edges at two different elevations, with the thin rods or wires set in the original position. During the motion, the film yields by sliding over the supporting thin rods or wires and the knife edges, being kept taut by elastic edge retainers on each side (not shown). In an alternative embodiment, the membrane is itself elastic with fixed mounting on the edges.

The mechanical arrangements discussed above can be used for solar energy harvesting, where, e.g. the components referred to as (11) in Fig.14b and (9) in Fig.16 are photovoltaic cells. Alternatively, they may be some type of thermo-electric element, feed-in points for light guides or thermal energy transport conduits. In certain applications the tilting panels may be mirrors that relay the solar energy to solar energy converters at other locations. In other applications, the tilting arrays may contain components that emit light instead. Examples of emissive arrays are directive illuminators and displays, which shall be treated in more detail later in this document. It may be noted by inspection of Figs. 14a,b and Fig.16 that these designs with a bar rigidly attached to several tilting elements lend themselves well to simple and low-cost manufacturing, since the bar allows precise and stable positioning of multiple components and their connections. Cf., e.g. emissive displays where each optical element ((10) in Fig.14a,b and (8) in Fig.16) shall receive an optical input different from that of its
neighbour: This typically requires large numbers of electrical wires leading to numerous individual light-emitting components. These wires can be laid out in parallel on the bars and led off the platform with a minimum of flexing during tilting and pointing operations. It can further be noted that the designs allow placement of active electronics in close proximity to the components, e.g. logic, switching and driver electronics in the case of displays and voltage converters and bypass diodes in the case of photovoltaics.

The present invention makes it possible to create pointing arrays in the form of array elements mounted on compact, low profile frames. Depending on the circumstances, e.g. shape, size and density of the elements in the array, the achievable tilt angles of the elements may be restricted to lower values than desired. In such cases, the frames carrying the pointing arrays may themselves be tilted about one, two or three axes, making use of the basic strategies taught in the present invention or other schemes. This can be used to extend the total tilt range of the array elements. In other cases, tilting of the frames may be used to simplify design or enhance performance. As an example of the latter, precision pointing towards a target can be performed as a two-stage process where the frame provides coarse adjustment and the array elements in the frame perform fine adjustment, e.g. by small-scale angular dithering (cf. discussion in conjunction with Fig.33a below).

Solar energy applications

Detailed descriptions shall now be given regarding how the teachings of the present invention can be implemented in the efficient capture of solar energy.
Common to the methods and embodiments is that they direct the energy-harvesting elements, e.g. solar panels, lenses or mirrors, towards the sun and adjust their pointing direction as the sun moves through the sky in order to maximize the amount of energy captured during the day. Three types of energy harvesting are treated in particular:

In the first category is the conversion of light to electrical energy by means of photovoltaic cells, where tracking optical systems concentrate the light onto smaller areas of photovoltaically sensitive surfaces, or where the photovoltaic surfaces themselves are kept facing the sun at optimal angle throughout the day. An indirect variant is where sunlight is relayed by tracking mirrors at one location and brought to impinge on a solar photovoltaic panel at another location.

In the second category is the capture of solar energy in thermal form. This may take place with the aid of concentrating optics to create high temperatures inside the tracking array itself, it may be part of a low-temperature thermal handling system, or it may involve relaying sunlight by tracking mirrors at one location onto a thermal solar energy collector at another location.

In the third category is the capture of sunlight and transmitting it to a remote point of use, typically for illumination purposes. Transmission may be by optical light guide that requires concentrating of the sunlight before transmission, e.g. an optical fiber, or it may be by free-space transmission from directive mirror arrays.

There shall now be provided a number of explicit
descriptions of embodiments where the mechanical principles described above are implemented for the purpose of solar energy harvesting. It shall be evident to the skilled person that whereas several of these embodiments are described with explicit reference to only one or two of the three general categories referred above, they may nevertheless be implemented in other modes as well.

Starting with the tilting-combined-with-rotation principle described above in conjunction with Figs. 10-18, the tilting panels panels may be flat solar cells that are maintained at optimal angle relative to the sun, or they may be optical elements designed to reflect or transmit light. Figs. 14a,b and Fig.16 show lens- or mirror-based solar concentrator embodiments: In the example shown in Figs. 14a,b the panels (3a-c) contain lenses (10) (here shown as Fresnel lenses) that focus sunlight onto photovoltaic cells (11) (or alternatively optical or thermal energy collector elements) located on a bar-shaped mount (12) that is rigidly attached by struts (13) to the panels (3a-c). Likewise, in Fig.16, the panels contain lenses (8) that focus sunlight onto photovoltaic cells (9) (or alternatively optical or thermal energy collector elements) located on a mount (10) below that is rigidly attached to the panels.

Flat, open frames with solar panel slats may be integrated into windows. Depending on circumstances (day/night, insolation, etc), the slats can be directed towards the sun for maximum electricity generation or they can be partially or completely closed (i.e. positioned flat in the plane of the frame) to control the amount of light passing through the window to the inside. In the latter case, a trade-off choice may have to be made
between power generation on the one hand and internal illumination on the other hand. In the case of strong insolation which may cause high temperatures and lower the photovoltaic conversion efficiency, the solar panel slats structure can permit efficient cooling by an air flow passing through it. At night, the slats can be closed to protect privacy, and in cold or hot weather the degree of opening may be selected for optimal heat transmission through the window opening.

Fig. 19 shows a preferred embodiment of the present invention as applied in a tracking solar concentrator application for photovoltaic energy conversion. Displayed is a cross-section of a trough-structure (2) carrying a lens (1) which captures and concentrates incoming solar radiation (3). The trough (the trough wall can be open except for support structure for the lens) is attached to a sphere (4) onto which a hollow tip extension (5) is attached. An upper plate (8) keeps the sphere in place via a circular shaped hole (6). A rod (7) which penetrates the hollow tip extension (5) is attached to a small sphere (14) at the opposite end. The sphere (14) is kept in position in the bottom plate (9) by means of a shaped hole (13). The bottom plate (9) can move in the x and y directions under the control of motors (12) positioned at two of its sides. The distance between the top plate (8) and the bottom plate (9) is fixed. This is achieved in this particular embodiment by permanently attaching the top plate (8) to the side walls of the surrounding casing (11), while the bottom plate is free to slide in the x and y directions with proper push/pull from the motors (12), e.g. via horizontal guides or openings (10) in the sidewalls of the casing (as is clear from descriptions above, alternative embodiments are possible as well
according to the present invention, where both the top plate and the bottom plate move each in its own
direction). A transparent cover (15) protects the solar concentrator device from dust, etc, and may also perform
optical filtering of incoming light.

The concentrating system functions as follows: If the lens (1) is positioned perpendicular to the incoming beams
(3) from the sun, the beams will converge towards the focal point (20) inside the trough structure. When the sun
moves, its position is tracked by the system via a sensor (16) which feeds its information via a processor/power
unit (17) and cables (18) to motors (12), which then move the bottom plate (9) in the correct x and y direction to
ensure that the lens always will be kept perpendicular to the solar beams (alternatively a micro-processor controls
the tracking position via time, date and latitude position, or the output power from the photovoltaic chip
(19) is maximized via a feedback loop). The lens obtains its correct position in this manner since the rod (7)
follows the x - y motions of the bottom plate (9), and by doing so, it is able to move the sphere (4)
correspondingly, and hence the trough (2) and the lens (1). The rod (7) slides smoothly in and out of the hollow
tip extension (5) in response to the x - y motion of the bottom plate (9).

Inside the trough a photovoltaic chip (19) is located near the focal point (21) of the lens (1) at the top of the trough. The closer the chip is placed to the focal point, the higher the concentration ratio and the smaller the required chip area will be. At the same time, the local thermal load on the chip will be high, the required pointing accuracy of the through will be high, and the
solar energy efficiency in diffuse light and overcast conditions will be low. As shown in Fig.19, it is possible to mount the photovoltaic chip in an alternative position (21) closer to the lens (1), whereby the local thermal load on the chip is reduced, the pointing accuracy requirements are relaxed, and light conversion in diffuse or overcast conditions is improved. In order to provide simple accommodation to different situations that may arise in practice, the side walls of the trough may have steps or mounting niches (22) at intervals from the top of the trough to the bottom where photovoltaic chip modules having different diameters can be attached at defined locations. Thus, the less concentration chosen (the closer the chip is to the lens), the wider the acceptance angle will be and the more diffuse light will be accepted.

The concentrating arrangement described may also allow other opportunities to reduce costs. The lenses (1) are typically circular and produce a circular spot of concentrated light on the chip (19). The silicon material used for the photovoltaic chip modules are grown from cylindrical ingots, which are first cut into thin slices, these again are cut into cell modules of desired shape and size. The latter operation typically reduces the silicon yield by at least 33%. This loss can be avoided if the ingot slices are used directly in circular form. In tracking solar concentrator systems, the size of the concentrated light spot is generally much smaller than the 6" ingot slice diameter commonly used as a starter before cutting into squares today. Growing smaller diameter ingots is less costly, and if the diameter is sufficiently small, e.g. < 1 cm, one may even envisage cutting circular slices from the ingot in a less material consuming way than is standard today, where as much as > 20% of the
ingot material is lost through the cutting process (mostly sawing into rectangular or polygon shapes).

In **Fig.19**, electrical contacting to the photovoltaic chip is based on a flexible conductor sheet (23). This sheet is able to fold sufficiently between the troughs (2) when they are tracking to allow a robust and inexpensive implementation, especially in cases where the number and spatial density of tracking troughs is high. The photovoltaic chips are typically attached to the conductor sheet before being integrated in the trough (2), via e.g. a standard pick and place process. The conductor sheet (23) is a priori equipped with printed electrical wires and thus functions as a flexible printed circuit board which can have other control circuitry onboard, e.g. for controlling voltage and current variations, DC/AC inverter conversion, etc. (24). As is evident to the skilled person, a flexible circuit board as described here is only one amongst several alternative ways of providing electrical contacting to a plurality of individual photovoltaic chips. One alternative is to employ metal wires connected to each chip, where the wires are led from the chip in such a way that they do not impede the motion of the pointing array, e.g. by feeding the wires through channels that penetrate the mechanical mounting means (spheres and rods) that support and rotate the trough (2), in analogy with the channels shown in **Fig.24** and **Fig.26** below. In certain cases, it may be advantageous to reduce the number of wires by using chassis conduction as common ground, as implemented in automobiles, etc.

The biconvex lens (1) shown in **Fig.19** is only one example of many optical systems that can be implemented in embodiments equivalent to that shown here. Other examples
of concentrating optics are shown in Figures 20a-20f, where in each case (1) is the photovoltaic chip and (2) is the optical concentrating element: In these examples, the concentrating element is a biconvex lens in Fig.20a, a Fresnel lens in Fig.20b, a holographic element in Fig.20c, a parabolic mirror in Fig.20d, a diffuse or specular reflector in Fig.20e, and a Cassegrain reflector in Fig.20f. As is evident to the skilled person, the examples shown are not exhaustive. Thus, combinations of the generic elements shown are possible, e.g. where reflecting surfaces are applied on refractive monolithic components in order to achieve robustness and simplicity. Furthermore, the concentrating elements may be combined with optical filters that transmit or reject certain spectral regions from the incident light, and diffuser elements may be incorporated to spread the illumination more evenly on the photovoltaic chip. Also, depending on the specific design and characteristics of the photovoltaic chip, it may be integrated into the optical structures in several ways to optimize performance. Thus, in Fig.20g and Fig.20h are shown configurations where chips of the bifacial type capture light from both the front and the rear side.

Simplified and miniaturised versions of the present invention as applied in photovoltaic solar power conversion are shown in Figs.21a,b,c. Here, light is captured by a plurality of lenses in the form of spheres that are arrayed between two plates or sheets. Each transparent sphere (1) focuses incoming light (2) onto a photovoltaic chip (3) which is attached to the sphere at the back wall near the focal point. When the direction of the incident light changes, the focus point will shift along the back wall of the sphere. In order to maintain
the illumination on the photovoltaic chip, the sphere is forced to rotate such that the position of the chip always coincides with the focus point. As shown in Figs.21a,b,c, this is achieved by confining each sphere between two parallel plates (5), (6) which can move relative to each other in a lateral direction. Three variants are shown:

In Fig.21a light passes through the transparent upper plate (5) and the sphere and is focused on the opposite wall of the sphere. The sphere is kept in position by a mild force keeping the upper and lower plates together, and when the plates move relative to each other, friction at the contact point (8) between the sphere and the top plate causes the sphere to roll in the shaped hole (7) in the lower plate (6). The photovoltaic chip is attached to flexible electrical wiring (4), e.g. in a conductor sheet with similar features as the flexible circuit board (23) described in connection with Fig.19. When the spheres roll in the holes (7), the connecting points for the wiring move in parallel causing some flexing but little stretching of the latter.

In Fig.21b the sphere (1) protrudes from a shaped hole (8) in the upper plate (5) and can rotate in this hole when the upper plate is translated sideways relative to the lower plate (6). Light rays (2) enter the sphere directly and are focused near the opposite wall of the sphere where it strikes a photovoltaic chip (3) which is attached to the sphere and connected electrically to flexible wiring (4), e.g. on a flexible conductor sheet. The latter is attached to the lower plate (6) at anchor points (9) positioned at regular intervals between the spheres. When the upper and lower plates move relative to each other in the lateral directions, the sphere is
brought to rotate due to lateral shearing forces acting upon it from the two plates, the upper plate from the sidewalls in the shaped hole (8), and the lower plate via friction and/or tugging forces from the attached conductor sheet.

In Fig.21c the sphere (1) is confined between the upper plate (5) and the lower plate (6). The situation in this case is very similar to that described in connection with Fig.21b, but now the lateral force from the upper plate is provided by friction between the top of the spheres and the top plate at the contact point (8).

While apparently quite similar, the embodiments in Figs.21a,b,c complement each other in various ways. Thus, the design in Fig.21a avoids involving the electrical wiring, etc in the function of transmitting rotating forces to the spheres, and provides opportunities for attaching the photovoltaic chip and electrical wiring after mechanical assembly of the plates and spheres. The design in Fig.21b employs top and bottom plates that need not be optically transparent, allowing the use of e.g. magnetic materials to provide a distributed attractive force between the plates (cf. discussion in connection with Fig.7a above). The design in Fig.21c employs top and bottom plates that are smooth and without holes, an obvious simplification. In all cases, the positions of the spheres relative to each other and relative to at least one of the sheets is defined by the holes in the sheets and/or via the attached flexible sheet (4). The embodiments shown in Figs.21a,b,c can span a large range of dimensions. In particular, the overall thickness can be made very thin (one millimeter or thinner). By using flexible top and bottom plates or sheets, the whole system
can become foldable, enabling numerous attractive portable applications.

**Fig. 22** shows an example of an important class of embodiments based on the teachings of the present invention, namely a **non-concentrating array of photovoltaic cells that are aligned such that they face the sun and track it throughout the day**. The photovoltaic chip (1) is positioned on a pedestal (3) which is attached to a sphere (4). An array of such spheres is kept in place between two planar sheets (5), (6) that can move laterally relative to each other under the control of a mechanical system (not shown), causing the spheres to rotate. As can be seen, the photovoltaic cell can be brought to face the incoming sunlight (2) by proper alignment of the two sheets (5), (6) relative to each other. Electrical connections are not shown in this figure. In such cases where no concentration of the incident light takes place but the chip surface is continuously oriented such that its surface normal tracks the sun throughout the day, the light collection efficiency may be increased by more than 30%, compared to a non-tracking photovoltaic chip module.

**Fig. 23** shows an application of the present invention where a tracking array of optical concentrator elements **converts solar radiation to thermal energy**. Each element in the array (of which only one is shown in the figure) is directed towards the sun and tracks it as it moves across the sky. In this example, the incident light (1) is concentrated by means of a parabolic reflector (2) which is mounted on a sphere (3). The latter is kept in place and subjected to controlled rotation by means of an upper plate (8) and a lower plate (9) that can move laterally relative to each other, and telescopic rods (5), (7)
connected with the sphere (4) that connects to the lower plate. A heat collector (6) is located at the bottom of the parabolic reflector (2). The detailed design of the heat collector may vary widely, and is not shown in Fig.23. Typically, it is covered by an efficient light absorbing material, and may be structured externally for optimal light trapping. In order to extract the collected thermal energy, a liquid or gaseous coolant is typically circulated through the element, transporting the thermal energy to points outside the array where it can be used in various ways, e.g. to heat water, air, gases, etc. Other types of thermal transport are also possible, e.g. thermal conduction in solid materials or in heat pipes or wicks. In certain designs very high temperatures can be reached at the focus, which can be used to generate thermophotovoltaic, thermo-electric or thermionic power, re-radiate infrared, etc. While not shown, flexible conduits for transmitting energy from the collector (6) may be led through holes in the base of the reflector to the space above plate (8), or through openings in the plates (8), (9) to the spaces between the plates or below plate (9). Alternatively, the telescopic rods (5), (7) may be hollow, providing a channel as shown in Fig.24 and Fig.26.

Fig.24 shows an application of the present invention where a tracking array of optical concentrator elements harvests solar energy and transmits it in the form of optical radiation to points of use inside or outside the array. Light (13) is concentrated by a lens (1) onto the tip of an optical fiber (18) located near the focal point (21). The light is guided through an optical fiber (18) from the focal point (21) to the point of use. In this particular example, the mechanical components of the
pointing array are as described in conjunction with Fig. 19, i.e. the sphere (4) rolls in a circular hole (6) in the upper plate (8) and a hollow rod (7) can slide inside the hollow tube extension (5) that is fixed on the sphere (4). The rod (7) is attached to the lower sphere (3) which can roll in a circular hole (11) in the lower plate (9). In Fig. 24, (17) indicates the presence of an optical filter in the light path, which may be employed in cases where it is desirable to modify the spectral content of the captured light, e.g. by removing ultraviolet or infrared radiation that may cause damage or reduce efficiency of the illuminated components. The filter may be incorporated into the structure as shown or may be integrated into the lens, a protective cover, etc in ways that are well known to the skilled person.

Light that is carried by the optical fiber can be put to use in several ways, e.g. electrical power generation and lighting. An example of the former is given in Fig. 24, where light (14) tapped from the end of the optical fiber (15) shines on the photosensitive surface of a photovoltaic device (10). Electrical power is extracted via the electrical leads (12). An example of the latter is indicated by the detail (16) in Fig. 24 showing an alternative fiber direction leading to a remote luminaire (not shown).

The present invention allows for many types of lighting applications. One implementation is shown in Fig. 25 where the embodiment illustrated in Fig. 24 is complemented by a mirror-image light emitting array at the other end of the optical fiber or light guide. Each of the receiving and emitting arrays has its own tracking system, allowing them to operate independently. Light from the sun
is tracked and captured by the lens (1a), and transported via the fiber (18) and through the trough (2b) to the opposite lens (1b), wherefrom it is beamed out as unconcentrated light. The direction of this lens (1b) can be controlled electronically, e.g. by remote control, allowing a single or an array of similar lenses to display sunlight wherever preferred, e.g. inside dark rooms in housing, etc. and in whatever direction. As shown, this system only works during direct sunlight. This directional lighting system may still be used after sunset, by placing another light source at the focal-point of the first lens system (6a), e.g. LED, and guiding the light through the optical fiber (18) to the second lens system (1b), from where it is beamed out in any selected direction.

System aspects for solar energy applications

A major aspect of the present invention is that it becomes possible to install tracking energy collectors in flat, slim panels that can be easily built into building facades, roofs, etc., and to deliver electrical power at prices that can compete with traditional grid power. This can have profound consequences, leading to a much higher level of integration between solar energy collectors and total energy management in buildings than has hitherto been practical.

In a typical prior art photovoltaic solar panel, only a relatively small fraction of the incoming solar radiation energy is converted to electrical power. The rest is either reflected back or converted to heat. High temperatures are detrimental to photovoltaic cell performance, and removal of heat is especially important in solar concentrator devices. This is typically done by employing cooling fins in passive systems. The present
invention provides simple means of harvesting heat for use in buildings, provided that the panels with the tracking collectors are included from the very start as an integral part of the building infrastructure.

An example is given in Fig.26, which shows a cross section through a tracking solar concentrator array according to the present invention, configured so as to fit within the form factor of a flat solar panel. Two plates (1), (2) can move laterally to align three sets of concentrator units (3) anchored by ball joints (4),(5) which are connected by hollow stems (6). The concentrator units (3) focus sunlight onto a photovoltaic cell (7). The cells (7) are actively cooled by an airflow as shown by the broken lines (8). A motor-driven fan (9) draws air into the chamber (9), and the resulting slight overpressure forces air through the hollow stems, impinging on the cells (7) before exiting into the space above plate (1). The fan may be supplanted by externally provided over- or underpressure. If such a panel is integrated into the wall of a building, it is simple to capture the heated air in the space above the upper plate (1), e.g. by enclosing the panel under a protecting glass plate above the panel (not shown), and guide the heated air through ducts within the wall of the building to a point where the heat energy can be extracted or stored, cf. below.

Fig.27 shows how tracking solar arrays according to the present invention can be integrated in the form of flat panels into the wall and the roof of a house. One of the panels (1) forms part of the roof. It has a transparent weather-resistant outer sheet (2) and is a modular part of the roofing itself. Incident sunlight (3)
is transmitted into the panel and strikes array elements (4) which are oriented optimally towards the sun and contain photovoltaic cells that convert light into electricity. As was the case with the panel shown in Fig. 26, an internal fan (not shown) circulates cooling air through the panel, drawing in air and exhausting it through the vents (5), (6). The other panel (7) forms a modular part of one of the walls in the house. As was the case with the roof panel (1), this one also has a transparent weather-resistant outer sheet (2) and array elements (4) which are oriented optimally towards the sun and contain photovoltaic cells that convert light into electricity. In this case, however, a coolant gas which may be e.g. air or argon is brought to circulate through the panel by means of over- or underpressure created by a module (8) positioned elsewhere in the house and communicating via ducts (9). When a gas other than air is used, it shall in most cases be desirable to recirculate the coolant gas in a closed system. In Fig. 26, the thermal energy from the panel is brought to a heat exchanger in the module (8), where the circulating gas can be cooled down and the thermal energy extracted. The latter can be performed in several ways, depending on the particular situation. Thus, the heat may be distributed throughout the house to provide area heating, or it may be stored in a thermal reservoir for later use. By employing a heat pump in (8), the temperature can be boosted at moderate energy expenditure. This makes possible heat storage at elevated temperature in high efficiency reservoirs employing latent heat or chemical transformation. Other types of applications may also become possible at high temperature, e.g. thermal generation of electricity. Further variations are possible, as can be appreciated by persons skilled in the
art. What is clear is that not only the photovoltaically useful spectral components in solar radiation can be captured for practical use, but a very large part of the total incident power.

Integration of tracking solar arrays according to the present invention into buildings and other static structures such as chimneys, masts, noise barrier walls etc may be motivated by low cost, low profile, high wind resistance, etc as previously described. There is an additional important attribute of tracking solar arrays according to the present invention which extends applicability yet further, namely agility: The moving masses involved and distances to be traversed during operation are typically much less in the case of arrays according to the present invention than in traditional solar trackers. This may not be important when tracking the sun from a ground-fixed position, in which case it is adequate to follow the sun as it moves through the sky at 15 degrees per hour. However, it may in many cases be desirable to mount a tracker on a moving platform such as a vehicle or a floating structure, in which case the slewing capability of the tracker must be much higher. This is illustrated in Figs. 28 a,b where tracking arrays are mounted on the roof of a car and on the roof and side of a boat. As the car follows a winding road and the boat moves through waves and alters its course, the tracking must be able to follow quickly in order to avoid losing its tracking locking, hence the importance of agility.

Thus, by adaptation of the present invention in different ways, it can be tailored to either focus on photovoltaic applications or offer full-spectrum solutions, exploiting different parts of the spectrum for
different usages. By doing so a very large part of the available solar energy can be utilized, making the system very cost competitive.

5 High efficiency solar power embodiments

In most prior art solar concentrator applications, the main reason for concentrating the sunlight onto a smaller area is to reduce the amount of costly photovoltaic solar material that is required, and possibly to achieve somewhat higher conversion efficiency than would obtain in a one-sun case. As shall be described in the present and following preferred embodiments, however, a range of novel and very significant solar energy capture schemes become possible once the light is focused in a predictable manner upon a small area. In order to benefit from such schemes one must employ solar tracking. The present invention is especially well suited in implementations where solar energy collectors are to be integrated into stationary structures such as the walls and roof of a house, where a flat, low profile architecture is required, and where the light capture area shall be covered with an array of small solar energy collectors where each is actively oriented such that it always points directly towards the sun.

25 Light trapping

In Fig.29 is shown one element in an array: This element is tracking such that the optical axis (11) points towards the sun. Light is captured by the front end optics (2) and focused to a small spot at the entrance (3) to a light-trapping structure (10). The light-trapping structure is a cavity with a small hole where light can enter, and with walls that can absorb and/or reflect light. As illustrated in Fig.29, a light ray (1) that
enters the cavity may be reflected again and again from the walls in the cavity, but has a low probability of escaping through the entrance hole since the latter constitutes a very small part of the entire wall area in the cavity. Thus, almost all light that enters into the cavity is ultimately absorbed in the walls. This type of structure is well known in the art and has been extensively used to create near-perfect blackbodies. In the present case, however, the main object is to maximize the interaction between the light that enters the cavity and selected areas on the walls of the cavity where the photovoltaic material is. As shall now be described, this can be achieved in different ways:

Assume initially that the cavity has the shape of a rectangular prism with six walls labelled 4, 5, 6, 7, 8, 9 as indicated in **Fig.29**. After passing the entrance hole (3) the ray (1) first strikes the wall (5). Light that is not absorbed in this first encounter is reflected downwards, subsequently bouncing off surfaces (6), (4), (5), etc. After a sufficient number of reflections, the ray shall escape through the hole (3), but by this time most of its energy has been spent. Thus, if all of the internal walls were covered by photovoltaic material, nearly all of the initial energy shall be absorbed in the photovoltaic material and a high conversion efficiency is achieved.

Consider now the case where only one of the walls in **Fig.29**, say wall (5), is covered by photovoltaic material while all of the other walls are high quality mirrors. If the ratio between the area of the entrance hole (3) and the total internal wall area of the cavity is a small number, the light shall once again bounce around inside
the cavity a very large number of times and losing energy every time it is reflected off wall (5) with the photovoltaic material. Thus, very efficient conversion of light into electric energy is achieved in this case also. Clearly, the same reasoning can be applied in the case where only a smaller area on one of the walls, rather than a whole wall, is covered by photovoltaic material.

In Fig.29 the walls of the cavity are shown as specularly reflecting. This needs not always be the case. As long as the ratio between the area of the entrance hole (3) and the total internal wall area of the cavity is a small number, one or more diffusely reflecting walls may still be used to re-direct light onto a photovoltaic-covered surface inside the cavity, provided the total hemispheric reflection coefficient is high. However, in certain applications, specular reflection shall be preferred since it can provide a higher degree of predictability and control.

Until now, the fate of the ray labeled (1) in Fig.29 has been studied in some detail. However, this ray only represents only a small part of the total light flux entering the free aperture of the lens (2). Near-parallel light rays from the sun that are captured and focused by the lens (2) onto the entrance hole (3) shall span a range of angles relative to the optical axis (11) as they enter the cavity (10), from zero and up to a maximum as indicated by the rim ray (1). Correspondingly, the pattern of reflections inside the cavity for the total captured light flux shall exhibit considerable complexity, but still in principle be predictable once the launching conditions of the bundle of rays entering at (3) are known, as well as the geometry and reflection/absorption
properties of the cavity walls.

As is clear from the above, a light trapping structure as the one shown in **Fig.29** can be used to enhance the absorption in photovoltaic cells that otherwise would lose much of their conversion efficiency potential through reflection. Before proceeding to a more detailed study of how this can be exploited for weakly absorbing thin-film photovoltaic cells, an important class of preferred embodiments shall be described:

**Tandem cells**

The tandem cell concept is well known in the art, and is illustrated in **Fig.30**. Briefly, it implies allowing incident sunlight to interact initially with a first photovoltaic cell (1) of high bandgap which makes efficient use of the high energy (short wavelength) photons (2). The below-bandgap photons which are not absorbed are allowed to exit this first cell and enter a second photovoltaic cell (3) behind it, which typically forms a stacked, e.g. monolithic sandwich structure together with the first cell as shown in **Fig.30**. This second cell has a lower bandgap, and can thus absorb the low-energy (long wavelength) photons (4) to generate electrical power. In this manner, the two cells in a tandem arrangement can achieve a higher total conversion ratio than a single cell with a single bandgap, where a trade-off must be made between losing below-bandgaps photons when selecting a high bandgap on the one hand and squandering photon energy to heat when selecting a low bandgap on the other hand. The basic idea of the two-cell tandem can be extended to encompass more than two different bandgap materials positioned in sequence behind each other, and very high conversion efficiencies have
been achieved by light transmission through stacks of lower-and-lower bandgap photovoltaic materials.

As shall now be described, a tracking concentrator/light trapping architecture of the basic form shown in Fig.29 provides new opportunities for constructing very high efficiency tandem-type solar cells:

Consider first the case where the walls (5) and (6) in Fig.29 are photovoltaic cells employing photovoltaic materials of types PV(1) and PV(2), respectively, whereas all other walls are high quality mirrors. PV(1) and PV(2) have different bandgaps and are complementary in the sense that they form a photovoltaic tandem pair, i.e.: much of the light which is not absorbed by the higher-bandgap PV(1) shall be absorbed if allowed to strike the lower-bandgap PV(2). In Fig.29, the ray (1) is shown to strike cell (5) first. If this cell contains a PV(1) type material and is backed by a light-reflecting electrode, the light which is below the bandgap for this material shall be reflected via the bottom wall (7) and onto the cell (6) containing PV(2) material. Here, the light that passed through cell PV(1) can now be absorbed and produce electric power. Any above-bandgap light that is reflected from photovoltaic cells in the cavity without being absorbed in a first pass is recirculated by multiple reflections inside the cavity, improving the overall conversion efficiency as described above. There remains, however, to consider the case of a light ray which enters the opening (3) from the opposite direction to the one shown for ray (1), striking the cell with the low-bandgap material PV(2) first. In this case, much of the light would be absorbed in this low bandgap cell, and a considerable fraction of the light would be lost as heat.
rather than being converted to electrical power. In the geometry of Fig.29, one can expect that roughly half of the photons that enter through the hole (3) strike the high bandgap material on wall (5) first and subsequently strike the low bandgap material on wall (6), yielding an efficient tandem pair. The other half of the photons can be expected to strike the low bandgap material on wall (6) first, yielding a lower efficiency than in the tandem combination. The overall efficiency shall depend on many factors, but in many cases, especially where there is significant first-pass reflection from the photovoltaic cells, the structure in Fig.29 with two different bandgap materials shall provide a higher conversion efficiency than a single material.

The above initial discussion highlights one of the differences between transmissive tandem cells according to prior art where light passes through two or more photovoltaic cells in succession, and reflective tandem cell architectures as shown in Fig.29: In the former case, the sequence of interaction with the lower-to-higher bandgap cells is taken care of by stacking the different materials in the correct sequence along the light path through a sandwich or monolithic block. In the latter case, the sequence of reflections must be set up such that the different bandgap materials are illuminated in the correct order. As shall be described below, the use of tracking concentrator architectures as taught in the present invention provides predictability and control over lightpaths which not only makes it possible to ensure correct illumination sequences in tandem-type solar cells, but also control over local illumination geometries at each cell.
Two basic examples of reflective tandem cell architectures in light trapping configurations are shown in Figs. 31a,b:

In Fig. 31a the light ray (1) is directed by the lens (2) towards the entrance hole (3) in the tandem cavity (8). A first, high bandgap photovoltaic cell (5) covers the wall opposite the entrance hole, whereby the entering light shall always strike cell (5) first. Light that is not absorbed in cell (5) is reflected towards a second, low bandgap photovoltaic cell or set of cells (4) located on the opposite wall where the entrance hole is. The sidewalls (6), (7) and other sidewalls (not shown) are highly reflecting surfaces that aid in recirculating light that is not absorbed during the first pass on the photovoltaic cells. As can be ascertained by tracing a set of different rays through the lens and entrance hole, nearly all of the light captured by the lens shall strike the cell (5), (4) combination in the correct order. The exception are rays that follow very closely along the optical axis of the lens, which are reflected back out of the cell through the entrance hole (3). Also, light that undergoes multiple reflections within the cavity without being absorbed can be lost through the entrance hole. If this hole is small compared to the other dimensions of the cavity, these effects shall be very small.

Fig. 31b shows another variant of a tandem cavity: The light ray (1) is directed by the lens (2) towards the entrance hole (3) in the tandem cavity (8). A first, high bandgap photovoltaic cell (5) covers the wall opposite the entrance hole, whereby the entering light shall always strike cell (5) first. In this case, the wall is slanting to the side such that all incoming light is directed onto cell (5) at a larger average angle of incidence than was
the case in Fig. 31a (this is beneficial in certain cases, as shall be discussed later). Light that is not absorbed in cell (5) is reflected towards a second, low bandgap photovoltaic cell (4) located on the opposite wall. In this way, there is no need to accommodate the entrance hole on the same wall as one of the photovoltaic cells. The sidewalls (6), (7) and other sidewalls (not shown) are highly reflecting surfaces that aid in recirculating light that is not absorbed during the first pass on the photovoltaic cells. As can be ascertained by tracing a set of different rays through the lens and entrance hole, all of the light captured by the lens shall strike the cell (5), (4) combination in the correct order, and light loss by multiply reflected, non-absorbed light that exits through the entrance opening (3) can be made negligible by proper choice of hole and cavity dimensions.

Monolithic, stacked tandem cells of the type shown in Fig. 30 have been reported where conversion efficiency is augmented by adding up to several more layers of photovoltaic materials with different bandgaps selected to form a sequence of values. An analogous extension to more than two different bandgap cell types is possible in the present case also, as can be appreciated by continuing the ray tracing after the two initial bounces against cells (5) and (4) in Figs. 31a, b, extending the cavity walls and covering the extended walls with lower and lower bandgap photovoltaic cells. Because of the angular spread of the light bundle entering the cavity through the entrance hole (3), such an approach shall in most cases imply that some of the light shall experience two or more reflections from a higher bandgap cell before reaching the next, lower bandgap cell. This need not represent any serious problem, however, since above-bandgap light reflected from a given
cell shall then have a renewed chance of being absorbed, whereas below-bandgap light shall only be weakly absorbed before being passed on to the next, lower-bandgap cell.

As shall be clear to the person skilled in the art, the basic idea illustrated in Figs. 31a,b can be varied in a large number of ways, whereby the combined principles of solar tracking, light trapping and tandem cells shall make possible the construction of photovoltaic solar energy conversion devices with very high conversion efficiencies. This shall become even more evident through the description which follows, where it is disclosed how the large fraction of glancing (high incidence angle) illumination of the photovoltaic cells that is typical in many of the described light trapping architectures can be crucial for boosting performance when thin-film photovoltaic cells are used:

Thin-film solar cells are of great importance and are expected by many to become the dominant type of solar cells in the future. Fig.32 shows a simplified principle drawing of an organic-based thin-film solar cell: A thin film of an organic photovoltaic material (1) is sandwiched between an electrode (2) made from a transparent, high work function material such as Indium Tin Oxide (ITO), and a metallic electrode (3) made from a low work function material such as aluminum. Electrical leads (4), (5) carry power from the cell to an external circuit. Light enters the cell through the transparent ITO and is partly absorbed in the thin film of organic photovoltaic material. The non-absorbed light strikes the reflecting back electrode and makes a return pass through the photovoltaic material. The part of the light that has not been thus absorbed exits the cell through the ITO and is
lost. A fundamental problem with these types of cells are that the organic photovoltaic material must be very thin (low charge carrier and exciton mobilities), and therefore absorbs only a small fraction of the incident light. This problem is compounded by the traditional prior art geometry where illumination is from free space and onto a planar sheet, typically straight down or nearly so. As shall become apparent in the following detailed description of a class of preferred embodiments of the present invention, significant improvement in conversion efficiencies can be expected by paying explicit attention to the detailed physics of light absorption in very thin films on highly conducting surfaces such as metallic electrodes.

In order to provide a better understanding of the following preferred embodiment of the present invention, a brief recapitulation of optical reflection-absorption processes in thin films on metallic surfaces may be useful: In Fig.33 two light rays (1) and (2) are incident upon a thin film of light-absorbing material (3) which lies on a metal surface (4) with high electrical conductance. Light ray (1) is incident normal to the surface, while light ray (2) has grazing incidence at angle θ. As is well known by practitioners of reflection-absorption spectroscopy, electromagnetic radiation is not absorbed in a film on a metal surface if: a) The film thickness is much less than the radiation wavelength, and: b) The metal is a very good electrical conductor, and: c) The incident electromagnetic radiation has no electric field (E-field) component perpendicular to the surface. Freely propagating electromagnetic waves such as sunlight have their E-field perpendicular to the ray direction. As the light strikes the surface of a very good electrical
conductor, any component of the E-field parallel to the
surface must form a zero node there. Since it is the E-
field component in the light that causes the absorption in
the thin film, it follows that significant absorption
shall only be obtained if the illumination configuration
is chosen correctly. Turning now to ray (1) at normal
incidence in Fig.33, one notes that both of the
polarization directions (indicated by arrows (5), (6)
normal to the ray direction) for the E-field in the light
are parallel to the surface. Thus all polarization
components in the incident light shall have a zero node at
the surface, and negligible absorption takes place in the
thin film. Ray (2) at grazing incidence is shown to carry
light of two polarization directions: One is perpendicular
to the plane of incidence and is marked by the tips of
arrows (6) (s-polarization) while the other is parallel to
the plane of incidence and is marked by arrows (5)
perpendicular to the ray direction (p-polarization). As
can be seen by inspection, only p-polarized light has an
E-field component perpendicular to the surface and can
survive in close proximity to it, and this component
increases as the angle of incidence, \( \theta \), increases. Thus,
in order to maximize absorption of light in the thin film,
the light should be p-polarized and arrive at a very flat,
grazing angle (large \( \theta \)).

Going back now to the light trapping architectures
described previously, it is immediately clear that these
architectures are well suited for maximizing absorption
when thin-film photovoltaic material is used in the cells,
since the architectures create grazing incidence by their
very design, and it is easy to design cavities where
incidence angles \( \theta \) are very large. However, the
polarization properties of the light should also be
considered: Sunlight is randomly polarized as it enters the tracking light concentrator, and it can in most cases be assumed that the light entering the light trapping cavity is also randomly polarized. Referring to Fig.29 as an example, the ray (1) first strikes the cell (5) on the right wall. If this cell is very thin and backed by a highly reflecting metallic electrode, the reflected light beam shall be depleted somewhat by absorption in the thin film, but this depletion shall mostly affect the p-polarized component of the light. In the right angled prismatic cavity of Fig.29, the light ray that impinges upon the cell (6) shall be further depleted in the p-polarized component of the light upon reflection from the left wall. After multiple reflections, the trapped light shall be more and more polarized, and only half of the light or less shall ultimately be absorbed in the thin-film cells. This is of course an extreme scenario. In practice, there are several reasons known to persons skilled in the art why the reflection from each cell and each mirroring cavity wall shall induce polarization change. Also, the ray (1) shown in Fig.29 is only one of a bundle of rays diverging in different directions towards the walls in the cavity, and many of these can be traced to show that even in the right angled prismatic cavity of Fig.29 there shall be significant polarization mixing and absorption in thin-film cells. However, there is always a competition between photovoltaically useful light absorption and other types of losses in the cavity, and it is important to ensure that the cavity is designed for optimum efficiency by taking this into account. One class of preferred embodiments is based on geometric design of the light trapping cavity: An example of this is is shown in Fig.34, where cavity walls are mutually positioned at skew angles in the shape of a pyramid to promote
polarization mixing. Here, (1) is the concentrating optics, (2) is a light ray, (3) is the entrance hole into the light trapping cavity, and (4), (5) are two of the external walls of the light trapping cavity. Another class of preferred embodiments is to promote polarization mixing by means of birefringent elements in the cavity, e.g. as coating on the walls. Yet another class of preferred embodiments is to position the thin-film photovoltaic material outside node regions by employing transparent spacer electrodes of lower conductivity between the thin-film photovoltaic material and the metallic electrodes.

Light trapping cavity structures

The cavities in Figs. 29, 31(a, b) and 34 can be created in a number of ways, e.g. by assembling a set of flat tiles to form cavity walls with the appropriate qualities. Alternatively, preferred embodiments of the present invention include cavities consisting of a monolith made from glass, plastic or another transparent material. The photovoltaic cells are in this case coated onto the outer walls of the monolith, or discrete cells are positioned in optical contact to these walls. Light that shall be admitted into the cavity can be controlled by small-area optical elements or coatings at the entrance hole, e.g. a shortpass heat rejection filter and/or an antireflection coating. Since the photovoltaic cells are illuminated by direct contact with the transparent medium in the cavity which has an index of refraction $\gg 1.0$, reflection losses shall in most cases be small. This is especially important in light trapping situations with grazing incidence (Fresnel reflection at interfaces increases strongly at large incidence angles).
Reflection and projection of light from array

Fig.35a shows a flat panel (1) containing an array of flat mirrors (2) that are aligned parallel to each other and can point and track in parallel by mechanical means as taught in the present invention. Near-collimated light (3) such as sunlight which falls upon the array is reflected as multiple parallel beams (4) in a direction determined by the instantaneous position of the mirrors in the array. The reflected light is directed onto another object (5), which may be, e.g. a flat solar energy collector panel which generates electricity, thermal power or both.

However, it shall be evident to the skilled person that the present discussion in connection with Fig.35a et seq. shall be relevant in many other types of situations where it is desired to reflect light from a directive mirror array onto a given area. One such example is where sunlight is redirected from a mountaintop and down into the city square in a dark valley below. More generally, the advent of flat, low cost, flexible mirror arrays according to the present invention may enable the creation of large scale cooperative networks for solar energy collection and distribution. This may encompass, e.g. a community of private homes, an industrial estate, a defined part of an urban landscape or other regions. Thus, one or more energy collectors of the photovoltaic or thermal type may be positioned within line of sight from mirror arrays that either redirect sunlight that illuminates them directly or relay light from yet other mirror arrays. In this manner, mirror arrays can be placed in sunny locations that otherwise would not be accessible or economically attractive for placement of photovoltaic or thermal energy converters, and form part of a solar energy harvesting system that covers large areas. One can discern many interesting consequences from this: Owners of
locations with good insolation may sell solar power from mirror arrays on their properties and direct reflected power onto energy converters owned by their customers. As the sun moves in the sky, some of the mirror arrays might be disengaged and new ones come on line. The photovoltaic or thermal converter may be static, e.g. of the flat plate type, or a concentrator which is direction sensitive. In the latter case, the receiver must re-direct itself during the switching from one mirror source to another, and may select which mirror source to collect energy from. In addition to providing a stabilizing effect on the illumination of the energy converters throughout a large fraction of the day, such schemes open up opportunities for owners of receivers and mirror sources to negotiate price for energy delivery and shop around for partners. Existing buildings and various structures could be unobtrusively retrofitted with mirror arrays. Overall, the amount, cost and stability of energy harvested from a given portion of a given urban landscape or suburban neighbourhood could be decisively influenced by such schemes.

If the incidence direction of the light upon the panel (1) changes, e.g. by the motion of the sun in the sky, the mirror array (2) automatically adjusts its pointing direction such that the reflected light still is directed onto object (5). There are many ways of achieving this, known to a person skilled in the art. Whereas use of preprogrammed look-up tables in conjunction with angle encoders and timers is a possible solution in certain cases, feedback control in closed loop shall generally be preferred in the present context due to the inherent flexibility and reliability:

- One method involving feedback control in a closed
loop is indicated schematically in Fig.35a, for the case where the object (5) is a solar photovoltaic panel. The instantaneous power generated in the panel is detected, and a signal encoder (6) generates a signal which carries information about the power level. The signal is fed back on a wired or wireless link (7) to logic circuitry (8) in the mirror array panel (1) which controls servos linked to the mirror array. To maximize the power level from the solar photovoltaic panel, small scale angular dithering of the mirror array may be used in conjunction with lock-in detection of the signal received on the link (7) in Fig.35a. In cases where two or more mirror arrays are trained on a common object (5) as exemplified in Fig.35b and Fig.36, optimization of the pointing direction of each array can in this case be achieved by having each array dither at a different frequency. Alternatively, one array at a time is optimized while the others remain stationary.

- In a variant of the above method, one or more photodetectors are located on or around the nominal reflection spot centroid position on the photovoltaic panel, and the signals carrying information on the light level are fed to the signal encoder (6) in Fig.35a. Alternatively, three or more photodetectors are located on the perimeter of the photovoltaic panel, whereby an imbalance in power levels between the photodetectors develops if the reflection light spot strays from a center position. Different types of logic schemes for optimizing the position of the reflection light spot on the photovoltaic panel in these applications are possible but are not described here, being known to persons skilled in the art.

- A different method involving feedback control in a closed loop employs a retroreflecting mirror positioned near the center of the photovoltaic panel, as shown in...
**Fig.35b:** Each of the reflector arrays (1a)-(1c) captures a portion of incident sunlight (3) and reflects it as bundles of light (4) that converge upon the photovoltaic panel (5). A retroreflector, e.g. in the form of a corner cube (6) as shown in the cut-out detail, is located in the center of the panel, and returns light onto photosensors (7a)-(7c) positioned near the center of each reflector array. When the reflector array is correctly aligned, the reflection light spot is centered on the retroreflector on the photovoltaic panel, and a directed light beam (8a)-(8c) returns to each reflector array. Here, it is detected by the photosensor (7a)-(7c) and a control signal is generated to enable the reflection array to maintain its correct alignment. This scheme is attractive when multiple reflection arrays are to be trained on a single target (photovoltaic panel) at the same time, since a single retroreflector on the target can provide selective feedback reflection to each of the multiple reflection arrays. Furthermore, no separate data link is required as was the case in Fig.35a. Finally, discrimination against detection of light striking the photosensors (7a)-(7c) from other sources than the retroreflector (6), e.g. direct sunlight, can be achieved by modulating the reflectivity of the retroreflector and/or employing direction-sensitive photodetectors.

The mirror array (1) in Fig.35a may in many cases be viewed as equivalent to a single large flat mirror which redirects incoming light onto the object (5), and the light flux density at (5) can at most approach the incident flux density upon the mirror array. However, when **several mirror arrays** placed in different locations redirect light onto the same object (5), a **concentration of flux density** is achieved, cf. Fig.35b and Fig.36.
Important applications of flux concentration include energy harvesting from sunlight, both by direct thermal means and by the generation of electricity. In the former case, it is generally desired to heat a working fluid to elevated temperatures or to vaporize it. In the latter case, it can be economically very attractive to use multiple mirror arrays that feed light to a single photovoltaic panel: The cost per m² of reflecting surface in a mirror array shall typically be much less than that of a photovoltaic solar panel (especially when total installation cost of the latter is considered), and conversion efficiency is typically enhanced when the light intensity is increased. If a photovoltaic solar panel ((5) in Fig. 35 b and Fig. 36) has already been installed, it can be enhanced by mounting mirror arrays within lines of sight at very low cost per added watt. Depending on the concrete situation in each given case, the distance between the receiving solar panel and individual mirror arrays may differ within wide limits, with maximum distances being determined by mirror parameters (flatness, diffraction, pointing accuracy), non-perfect collimation of sunlight and other factors well known to persons skilled in the art of optics, as well as practical issues related to the concrete situation in each case. If the approximate distance is known a priori, the individual mirrors in the array can be selected to have a size and surface shape (e.g. slightly concave) which yields optimal illumination of the target. Despite the typically higher cost per effective area of photovoltaic material as compared to that of reflectors, it may in certain situations be advantageous to make the target area somewhat larger than the nominal spot size of the reflected light at the target, to capture outliers in the reflections from any array mirrors that are misaligned.
This may be particularly relevant in concentrator-type configurations where multiple arrays illuminate a single target (cf. discussion below, related to Fig.36).

Fig.36 shows a configuration which is a special case of that discussed in conjunction with Fig.35a: Multiple mirror arrays (1a)-(1d) according to the present invention illuminate a common target, in this case a photovoltaic array (6) covering the lower part of a support panel (5) which is mounted on a pedestal (7). Incoming parallel bundles of light rays (3a)-(3d) are reflected in parallel beam sets (4a)-(4d) from sets of tilted mirrors (2a)-(2d) and impinge on the photovoltaic array (6). Alignment and tracking issues are similar to those discussed in conjunction with Fig.35a.

When multiple reflector arrays are brought to illuminate the same receiving surface as illustrated in Fig.36, a concentration of power density occurs which in principle may reach very high levels, depending on the number of reflector arrays and configuration. A well-known problem in concentrating solar photovoltaic systems is the temperature rise due to dissipation of solar radiation that is not converted to electricity. In addition to the possible thermal damage in the photovoltaic cell and surroundings, high temperatures typically reduce the power conversion efficiency, and active or passive cooling is generally required to avoid this. In the present case, the individual mirrors in the pointing array (e.g. mirrors (2a-2d) in Fig.36) can be prepared in such a way that only those "useful" spectral components in the sunlight that contribute efficiently to electrical power generation in the photovoltaic array (e.g. (6) in Fig.36) are reflected. Alternatively, a protective window covering the pointing
array (not shown in Fig. 36) can be prepared such that it selectively transmits the "useful" spectral components while other spectral components are absorbed and/or reflected. In the latter case, reflection from the protective window shall not strike the photovoltaic array, since the array mirrors are generally tilted to some degree from normal reflection in order for the reflected light to strike the photovoltaic array.

The concept of concentration by the use of multiple reflector arrays provides great flexibility. It is simple to upgrade an existing system by addition of more reflector arrays, and reflector arrays can be located at positions having different distances and line-of-sight angles, to accommodate local situations. Additional simplicity and flexibility can be achieved by employing free-standing reflector arrays, i.e. units that operate completely without external wiring: The electrical power requirements in each reflector array consist of one component performing mechanical alignment of the mirrors and another component performing communication and logic functions. In systems based on the present invention, this power is typically orders of magnitude lower than the solar energy illuminating the array, and can easily be provided by a photovoltaic panel taking up a small area of the reflector array in conjunction with a small back-up battery. Wireless communication between the target and each reflector array as indicated in Fig. 35 shall be short range and can be set up by means of a number of well-established communication modes including infrared and radiofrequency communication in "free" (i.e. unregulated) bands. In addition to simplicity and increased flexibility, the complete absence of any external wiring makes it possible to create new types of
systems, e.g. reflector arrays within sealed enclosures such as double glazing cavities.

**Fig.37** shows an example where the generic configuration of **Fig.7a** is used in a reflector arrangement: A set of spheres (3) are kept in place between an upper sheet (1) and a lower sheet (2), e.g. by magnetic means as discussed in conjunction with **Fig.7a**. When the sheets are translated relative to each other, friction between the spheres and the lower sheet causes the spheres to rotate in parallel, sliding in the holes in the upper sheet. Each sphere carries a mirror (5) on a pedestal (4), and incoming light (6) is reflected from the mirrors as shown.

**Fig.38a** shows an embodiment similar to that in **Fig.37**. (1) and (2) are upper and lower sheets that can translate relative to each other, and (3) are spheres that roll between the sheets. Here, however, each sphere has a flat, mirroring part (4) which reflects incoming light (5). In this case, the mirroring area and maximum deflection angle are typically less than what can be achieved with the arrangement in **Fig.37**, but implementation is generally much simpler. Thus, the flat portion of each sphere can be made after round spheres have been assembled between two sheets, by keeping the sheets immobile while grinding the tops of the protruding spheres in the upper sheet against a flat grinding surface, followed by a polishing step.

**Fig.38b** shows yet another similar embodiment: Again, (1) and (2) are sheets that can translate relative to each other. Each sphere (3) has a thin, transparent wall and carries a mirror (4) inside which is fixed to the sphere
and rotates with it. Incident light (5) enters the sphere, is reflected from the mirror inside and exits again as shown. For simplicity, details of the wall and reflection/refraction at the wall are not shown. As is clear to the person skilled in the art, equivalent variants of this example are possible, e.g. spheres that are massive below the mirror. Comparing with the case shown in Fig.38a, larger mirroring areas and deflection angles are achievable, at somewhat increased cost in complexity.

In addition to their inherent simplicity, the embodiments illustrated in Figs. 38a,b provide interesting opportunities for making very thin devices with directional reflection control. By employing small spheres, the overall thickness may be made in the millimeter to micron range, and required translation range for full scan shall be correspondingly small. This in turn allows for the use of small-range, low power translation transducers employing, e.g. electrostriction or piezoelectric effects. When the devices are very thin, they must be kept in the desired shape by being adhered to a reference surface, e.g. a flat solid, or by being stretched in a frame. Flexible, very thin sheet-like embodiments can be adhered conformally to non-flat surfaces, e.g. parabolic surfaces, to provide means for actively correcting or modifying the reflective properties of the latter. Furthermore, flexible very thin sheet-like embodiments can be rolled up and deployed in applications where this proves important or useful.

Fig.39 shows an example of a free-space light beam relaying and switching system. In this case sunlight (2) is captured by a mirror array (1) mounted on the roof of a
building and directed into the house through a skylight (3). The latter is shown as an unprotected opening, but shall typically be a window of some kind. Once inside the house, the light beam (11) is directed by relay mirror arrays (4), (5), (6), (7) to the region (10) that is to be illuminated. Other types of relay optics known to persons skilled in the art may be employed to correct or modify the light beam characteristics as it travels through the house, e.g. a lens pair (8) which enables a wide collimated beam to pass through a small aperture, or to change its width. As the sun moves in the sky, the mirror elements in the array (1) adjust their pointing direction so that the light beam continues to strike array (2). The downstream arrays (2), (3), (4) etc may take part in fine tuning the path of the light for optimal light transmission through the relay system. More generally they can be used as switching elements to direct the light to different locations. In Fig.39 this is illustrated by the beam shown by broken lines (12), which results when the pointing direction of array (5) is changed from that used to reflect the beam (11). The beam (12) strikes a fixed mirror (13) which directs the beam onto a luminaire (14), i.e. an optical system which acts as a lamp fixture and distributes the light for illumination of the area (15).

Instead of such a fixed illumination system, the mirror array (7) can function as an active luminaire which can direct light in different directions as desired by the user (16), cf. the alternative lighting direction shown by the broken lines (17). Such arrangements can have many specialized uses, e.g. tracking persons who move about within a room. As shall be evident to the person skilled in the art, the basic ideas illustrated in Fig.39 can be applied in many other contexts. For example, the systems may be employed in locales other than buildings, such as
in outdoor environments, tunnels, etc, and the light source may be artificial rather than sunlight. Furthermore, pointing mirror arrays can form routing components in optical relay systems used for free-space optical data transmission. Finally, the reflectors may be optimized for a variety of radiation types, e.g. infrared or microwave.

An important class of embodiments of the present invention concerns projecting light that is generated in or routed into elements in a pointing array. The light can be directed in specific directions for a variety of purposes, including illumination of limited areas, marking/tagging of moving persons, vehicles, etc, and directional displays. Certain preferred embodiments shall now be described:

Fig.40 shows part of an emissive array where near-collimated light (1) is emitted from multiple pointing elements (2) as parallel light beams. The direction of the light beams is determined by the relative positions of sheets (3) and (4), cf. the description of the mechanically similar system in Fig.26. Each element contains a light source (5) positioned near the focal point of a lens (6), thus causing collimation of the light. Each light source is connected to a power source (7) by a set of wires (8). If the light sources (5) in all pointing elements (2) are activated in the same way from the power source (7), the wiring can be much simplified by using common leads and only a single power connection to the power source. In such cases the array can act as a pointing searchlight or beacon in a flat package. This can be particularly useful where a low profile is required, e.g. in various types of vehicles or in buildings, and may
enable novel applications. Thus, tracking illumination that follows a person in selected locales may be mounted flush into walls or ceilings, and lighting panels with directivity that varies throughout the day or according to circumstances may be integrated into homes, workplaces or public spaces.

By activating each light source individually, the array shown in Fig.40 can act as a display where each element (2) constitutes one pixel as seen from afar. Generally, the resolution and information content of the display shall depend on the number and properties of the elements in the array, as is well known in the art. However, in the present case the display shall have certain unusual characteristics which can be important in some applications:

a) Extreme brightness. Viewers located in the direction where the array is pointing shall observe a very high apparent brightness, which may permit reliable reading of displayed messages in situations where an ordinary array would be overwhelmed by other light sources.

b) Selective viewing. Only observers within the projected light bundle shall be able to see the message. This may be useful when it is desired to single out a specific group of viewers amongst many, or when it is desired to avoid disturbing people located in certain directions as seen from the array.

It should be clear to the person skilled in the art that the design showed in Fig.40 is just one example of many possible based on the present invention: The light source may be of any type that permits collimation of light by an optical system, i.e. preferably of high intensity and
small physical size. It may generate light in situ e.g. luminescent, incandescent, gas discharge, laser, or it may be the emitting end of a light guide, e.g. an optical fiber that is fed light at its other end. The collimating optics may be refractive, reflective, diffractive or a combination of these, etc. Finally, the mechanics controlling the pointing function may be of any type within the scope of the present patent.

Motion control in large scale arrays

In many applications it is desired to position several array panels side by side, e.g. when the area is to be covered with arrays is larger than can easily be achieved with a single array panel. As disclosed below, many embodiments of the present invention lend themselves well to scaling by mechanically linking the motor drives. An example is shown in Fig. 41, where 12 individual array panels (11)-(34) are arranged in a 2-dimensional matrix. A motor (1) translates the shafts (Y1)-(Y3) in the y direction, and a motor (2) translates the shafts (X1)-(X4) in the x direction. At each panel, an x-motion linkage is connected to one of the shafts (X1)-(X4) such that a translation in the shaft causes an array tilt in the x direction. Likewise, an y-motion linkage in each panel is connected to one of the shafts (Y1)-(Y3) such that a translation in the shaft causes an array tilt in the y direction. Thus, all arrays in the panels will tilt and point in parallel when the two motors (1) and (2) are activated.

Several embodiments can be made based on variants of this basic scheme. One is where the linear motion of the shafts is supplanted by a rotating motion of a screw. Another is where the shaft or screw is not one monolithic
piece, but several joined parts. In the latter case, each panel may have a force or torque transmitting member traversing it, ending in mechanical coupling points on opposite sides where linkages can be attached for transmitting force or torque to neighboring panels.

As described so far, all arrays in all panels would experience the same amount of angular motion, although one can envisage that the pointing directions of separate array elements or groups of elements need not be parallel. In a further class of embodiments of the present invention, the different panels (11)-(34) can be addressed matrix-wise such that they point in separate directions. One example of where this would be necessary is shown in **Fig.36**, where different panels of mirror arrays are required to adjust mirror angles in different ways. To achieve this, the linkage of each panel in **Fig.41** to the x- and y-drive can be enabled or disabled via an x-and a y-clutch (not shown). When the elements in a given panel are to be set to a specific pointing direction, a signal is provided which activates the clutches in that panel and the X- and Y-motors are activated as needed. Thus, all arrays in all panels can be set sequentially to the desired positions. In certain cases, more than one panel can be set at a time, e.g. when a whole row or column in the array shall move in the same fashion.
Claims

1. A multi-element two- or three-axis pointing array comprising at least two direction-critical elements capable of receiving and/or transmitting and/or reflecting electromagnetic or acoustic radiation and further comprising mechanical parts for motion control, wherein at least two elements in the array are adapted to exhibit a pointing motion by rotating about two or three axes and point substantially in parallel with other elements in the array, wherein said pointing array is adapted to be contained within a flat package, i.e. with all mechanical parts confined within a form factor where one dimension is substantially smaller than the others,

characterized in that

- said at least two elements are connected by a first set of mechanical links to a first of at least two driver bodies,

- said driver bodies are structures where all constituent parts have fixed spatial relationships relative to each other,

- said first of at least two driver bodies extend across the area that is covered by said array,

- said at least two elements are connected by a second set of mechanical links to a second of said at least two driver bodies,

- said mechanical links confine said at least two elements in predictable and defined spatial relationships to each other and to said driver bodies, and

- said at least two driver bodies can execute translation and/or rotation within a set of mechanical degrees of freedom defined by said mechanical links and/or mechanical guiding elements.
2. A multi-element pointing array according to claim 1, where said mechanical links are in the form of a rolling, slide-guided, pivoting or hinged connection between each of said at least two of said elements and said first and second driver bodies.

3. A multi-element pointing array according to claim 1, where said pointing array is adapted to be contained within a flat package, i.e. with all mechanical parts confined within a form factor where one dimension is smaller 3 cm or preferably smaller than 1 cm.

4. A multi-element pointing array according to one of the claims above, where said pointing array is adapted be integrated in a constituent element intended to form part of a static structure like a building or of a movable object like a vessel or a vehicle.

5. A multi-element pointing array according to claim 1, wherein said at least two of said elements derive all driving force for executing said motion from a mechanical link with said at least two driver bodies that can translate and/or rotate relative to each other.

6. A multi-element pointing array according to one of the claims above, wherein each of said at least two of said elements is linked at a pivot point, to each of at least two of said driver bodies.

7. A multi-element pointing array according to one of the claims above, wherein at least one of said at least two driver bodies is essentially planar.
8. A multi-element pointing array according to one of the claims above, wherein said at least two driver bodies retain their orientation relative to each other during the pointing motion.

9. A multi-element pointing array according to one of the claims above, wherein said at least two driver bodies are essentially planar and parallel and subject to mechanical restraints to minimize any differential rotational motion about a common axis normal to said essentially planar and parallel structures.

10. A multi-element pointing array according to claim 9, wherein said mechanical restraints comprise torsion bars and/or hinges.

11. A multi-element pointing array according to claim 10, wherein a first set of torsion bars and/or hinges support a first essentially planar structure, and a second set of torsion bars and/or hinges support a second essentially planar structure, wherein said first set of torsion bars and/or hinges rotates about at least two parallel but separated rotation axes directed along the x axis in a Cartesian coordinate system and where at least one of said axes is fixed to a support structure and at least one of the second of said axes is fixed to said first essentially planar structure; wherein said second set of torsion bars and/or hinges rotates about at least two parallel but separated rotation axes directed along the y axis in said Cartesian coordinate system and where at least one of said axes is fixed to a-support structure and at least one of the second of said axes is fixed to said second essentially planar structure.
12. A multi-element pointing array according to claim 9 or 10, wherein said mechanical restraints comprise at least one of a first and a second set of linear sliding guides, wherein said first set is restrained to move in the x direction in a Cartesian coordinate system and said second set is restrained to move in the y direction in said Cartesian coordinate system.

13. A multi-element pointing array according to claim 12, wherein said linear sliding guides comprise slits and/or swallow-tail guides and/or linear roller bearings.

14. A multi-element pointing array according to claim 7, wherein at least one of said essentially planar structures is in the form of a flat or corrugated solid plate, and/or a honeycomb structure, and/or a mesh, and/or a truss structure, and/or a frame with stretched wires.

15. A multi-element pointing array according to one of the claims above, wherein said elements are linked at pivot points in a first of said at least two driver bodies and via a mechanical connection at other points in a second of said at least two driver bodies.

16. A multi-element pointing array according to claim 15, wherein at least one of said pivot points is defined by a ball joint or a rod penetrating through a hole with elastic lining or an elastic membrane surrounding said hole.

17. A multi-element pointing array according to one of the claims above, wherein each of said at least two of said elements has a first sliding and/or rolling pivot point link at a localized position on a first of said
driver bodies, and comprises a rigidly attached rod-like part which passes through a guiding track or slot on a second of said driver bodies and a guiding track or slot on a third of said driver bodies, said guiding tracks or slots on said second and third of said driver bodies always maintaining a geometric relationship such that the spatial orientation of said rod-like part is uniquely defined.

18. A multi-element pointing array according to claim 17, wherein said second of said driver bodies and said third of said driver bodies can translate in two mutually non-parallel directions.

19. A multi-element pointing array according to claim 17, wherein said third of said driver bodies can execute a rotating motion relative to a fourth structure.

20. A multi-element pointing array according to one of the claims above, wherein a first of said at least two driver bodies can rotate about a first axis, and wherein said first of said at least two driver bodies carries two or more elements that can rotate about axes that are not parallel to said first axis and preferably substantially normal to same, said elements being mechanically connected to a second of said at least two driver bodies which is attached to said first of said at least two driver bodies, and wherein said second of said at least two driver bodies can execute a translatory and/or rotating motion relative to said first of said at least two driver bodies, said translatory and/or rotating motion acting via mechanical linkages upon said elements and causing them to tilt in synchronism.
21. A multi-element pointing array according to claim 20, wherein said elements are shaped, or rigidly connected to each other, to constitute longitudinal structures in the form of panels, slats or frames.

22. A multi-element pointing array according to claim 21, wherein said longitudinal structures are rigidly connected to functional components at a defined distance from said longitudinal structures, for the reception or emission of electromagnetic or acoustic radiation.

23. A multi-element pointing array according to claim 20, wherein said first of said at least two driver bodies is a rectangular or curved open frame, and wherein said second of said at least two driver bodies is a rigid linear or curved object.

24. A multi-element pointing array according to claim 20, wherein said first and said second of said at least two driver bodies are open frames that are hinged together by rigid linkages, and wherein said rigid linkages are rigidly connected at one end to said elements.

25. A multi-element pointing array according to claim 24, wherein said rigid linkages are tilted relative to each other at progressive angles, wherein each of said elements is tilted relative to the rigid linkage on which it is connected so as to present the same pointing direction in space at all times.

26. A multi-element pointing array according to claim 9, wherein said driver bodies are in the form of sheet-like objects which are kept apart by a plurality of spacer objects confined between said sheet-like objects, where
each spacer object presents a spherical or cylindrical surface at the contact points against sheet-like objects and can roll when said sheet-like objects are translated parallel to each other.

27. A multi-element pointing array according to claim 26, wherein said spacer objects are spheres or part of spheres that incorporate direction-critical elements within or on the spacer object itself, on rigidly attached protrusions, pins or rods, or on flexible and/or elastic material attached to the sphere wall.

28. A multi-element pointing array according to one of the claims 26-27, wherein each of said spacer objects rolls against a smooth surface on one of said sheet-like objects and rolls in the confinement of a hole or pit on the other of said sheet-like objects.

29. A multi-element pointing array according to one of the claims 26-28, wherein at least part of each said spacer object is optically transparent.

30. A multi-element pointing array according to one of the claims 26-29, wherein said sheet-like objects are kept together by magnetic, electrostatic, elastic or pneumatic forces distributed across their surfaces.

31. A multi-element pointing array according to one of the claims above, wherein said multi-element array is adapted to be mounted in a mechanical structure which can tilt and/or translate the array itself.

32. A multi-element pointing array according to one of the claims above, wherein said array is powered via one or
more translating and/or rotating mechanical linkages to one or more mechanical power sources and shares said power sources with one or more other arrays.

33. A multi-element pointing array according to claim 32, wherein said array can transmit mechanical power to other arrays via one or more mechanical linkages integrated into the array.

34. A multi-element pointing array according to claim 32, wherein said array is adapted to be arranged along a linear mechanical power shaft that translates and/or rotates, or near the points in a two-dimensional matrix where two sets of mechanical power shafts cross each other.

35. A multi-element pointing array according to claim 34, wherein said array is adapted to pick up mechanical power from said mechanical power shafts in one of the following ways: By permanent hook-up of all elements, or by engaging/disengaging a connection for one array or a subgroup of arrays in the matrix at a time.

36. A multi-element pointing array according one of the claims above, wherein said array is self-powered; i.e. the array is operated based on power produced by the array itself.

37. A multi-element pointing array according to one of the claims above, wherein at least one of said direction-critical elements alters its pointing direction as a function of the angular position of the sun or another physical or virtual object.
38. A multi-element pointing array according to claim 37, wherein directional tracking input is obtained from one or more radiation detectors in conjunction with logic circuitry, where said detectors intercept electromagnetic or acoustic radiation emitted or scattered from said object and determine its direction of incidence towards said direction-critical elements.

39. A multi-element pointing array according to claim 38, wherein said detectors are of the quadrant- or other direction-sensitive type.

40. A multi-element pointing array according to claim 38 or 39, wherein said detectors are located in at least one of said direction-critical elements.

41. A multi-element pointing array according to claim 37, wherein tracking is achieved by means of logic circuitry, position encoders and servo hardware, said logic circuitry deriving trajectory and timing information from a stored program, said program being either pre-loaded or generated in said logic circuitry by a learning algorithm.

42. A multi-element pointing array according to claim 37, wherein said array comprises on-board logic and/or memory and/or electrical power storage facilities.

43. A multi-element pointing array according to claim 37, wherein said direction-critical elements comprise photovoltaic elements.

44. A multi-element pointing array according to one of the claims above, wherein at least one of said elements
comprises an optical structure for controlling and
directing light.

45. A multi-element pointing array according to claim 44,
wherein said optical structure comprises refractive and/or
reflective and/or holographic and/or diffractive and/or
absorptive and/or fluorescent and/or spectrally selective
optical components.

46. A multi-element pointing array according to claim 45,
wherein said optical components comprise one or more of
the following: spherical simple or compound lenses,
transparent monolithic objects in the form of spheres
and/or light guides, holographic lenses, mirrors, Fresnel
optics, edge- or bandpass- or greytone optical filters,
optical modulators, polarizers.

47. A multi-element pointing array according to claim 44-46,
wherein said optical structure reflects incoming light
onto a target at some distance from said array, and
wherein said target is provided with means to generate
feedback information on the amount of light that strikes
the target, and wherein said feedback information is
transferred to a processor which controls the motion of
said direction critical elements.

48. A multi-element pointing array according to claim 47,
wherein said target receives solar energy and has one or
more of the following capabilities: Generation of
electricity, conversion to thermal energy, simultaneous or
sequential relaying of light energy in a linear or
branched optical relay chain.
49. A multi-element pointing array according to claim 47 or 48, wherein said means to generate feedback information comprises one or more photodetectors or temperature sensors.

50. A multi-element pointing array according to claim 47-49, wherein said feedback information is transferred from said target to said processor via a wired or wireless link or an optical fiber.

51. A multi-element pointing array according to claim 47-50, wherein said means comprises one or more retroreflectors.

52. A multi-element pointing array according to claim 44, wherein said optical structure contains a light source such as incandescent and/or light emitting diode and/or laser and/or fluorescent and/or light guide.

53. A multi-element pointing array according to claim 52, wherein light emitted from said light source is collected by an optical system within said element and is projected as a light beam from said element in said multi-element pointing array.

54. A multi-element pointing array according to claim 53, wherein said light beam from said element is essentially collimated and parallel to the light beam from at least one other element in said multi-element pointing array.

55. A multi-element pointing array according to claim 54, characterized in that said multi-element pointing array constitutes a directive searchlight or illuminator.
56. A multi-element pointing array according to claim 53, wherein the light intensity and/or colour from said light sources in said elements can be independently controlled.

57. A multi-element pointing array according to one of the claims above, wherein said multi-element pointing array is an acoustic or electromagnetic energy collector where radiation incident upon said multi-element pointing array is concentrated by radiation concentrator structures in at least two of said direction-critical elements and brought to impinge on materials and/or structures which capture at least some of the radiant energy incident upon them.

58. A multi-element pointing array according to claim 57, wherein said radiation concentrator structures comprise of one or more lenses and/or mirrors which concentrate electromagnetic radiation in the form of a focal point, focal line or extended spot.

59. A multi-element pointing array according to claim 57 or 58, wherein said materials and structures convert incident radiative energy into electrical power.

60. A multi-element pointing array according to claim 59, wherein said materials and structures comprise a light trapping cavity, said light trapping cavity having an entrance opening for admitting light, one or more photovoltaic elements, and cavity walls that are highly reflecting where not covered by said photovoltaic elements.

61. A multi-element pointing array according to claim 60, wherein said light trapping cavity has a light reflection
geometry wherein light is reflected from internal surfaces in a predefined sequence.

62. A multi-element pointing array according to claim 60, wherein said light trapping cavity has a geometry wherein an incident light beam reflects at different incidence angles and/or polarization conditions when undergoing multiple reflections within said cavity.

63. A multi-element pointing array according to claim 60, wherein said light trapping cavity contains two or more photovoltaic elements with different and complementary optical absorption characteristics.

64. A multi-element pointing array according to claim 57, wherein said detector materials and structures convert incident radiative energy into thermal energy.

65. A multi-element pointing array according to claim 57, wherein said array is encased in a closed volume suffused by a gaseous coolant which is guided by a pressure gradient past or through said antenna or detector materials and structures.

66. A multi-element pointing array according to claim 57, wherein said materials and structures form electromagnetic guide- or relay elements which can transmit electromagnetic power to points outside said concentrator structures.

67. A multi-element pointing array according to claim 66, wherein said guide- or relay elements comprise an optical fiber or microwave waveguide.
68. A multi-element pointing array according to claim 66, wherein said points outside said concentrator elements are located in one or more illumination or re-radiation structures.

69. A multi-element pointing array according to claim 66, wherein said points outside said concentrator elements are located in one or more structures which convert incoming radiation to electrical or thermal energy.

70. A multi-element pointing array according to one of the claims above, wherein said multi-element pointing array contains mirrors and reflects sunlight onto a solar energy collector or mirror-based relay- or illumination device at a location removed from that of said multi-element pointing array.

71. A multi-element pointing array according to claim 70, wherein said solar energy collector or mirror-based relay- or illumination device is direction sensitive.
Fig. 1a

An Amonix 25 KW MegaModule HCPV System at Nevada Power in Las Vegas. It is a part of a 75 KW installation. Source: Amonix

Fig. 1b

Photograph of the grid-connected CPV system using FLATCON®-type modules on top of the roof of Fraunhofer ISE. In Europe, this is the first CPV demonstration system using III-V cells.
Fig. 1c

Multiple arrays are assembled in a rotating platform that floats on a shallow layer of water with an evaporation barrier. This allows low-torque rotation, cooling and level operation.

Two-axis tracking
The troughs are arranged close to each other. They are combined on a platform, which rotates around its vertical axis with azimuthal travel of the sun. The platform is floating on a shallow body of water. Each-floating trough tracks solar elevation by tilting up and down.

Fig. 1d

Reflective troughs combined with directional lenses maximize solar coverage.

Heliotube uses 88% less PV material than traditional panels, resulting in a more cost-effective solar solution.

Tracking Solution for the Rooftop:
Heliotube's concentrators have integrated tracking built into the panel, enabling non-penetrating roof mounting and more uniform power throughout the day.

Silicon solar cells are the most expensive part of today's solar panels. Heliotube substitutes much of the costly photovoltaic material with inexpensive optics to focus the equivalent light onto small solar cells.
Fig. 1h

Embedded Rotatable Mirrors in a Concentrator
Figs. 4a, b, c

Fig. 4a

Fig. 4b

Fig. 4c
Figs. 9a,b

Fig. 9a

Fig. 9b
Fig. 11
Figs. 14a, b

Fig. 14a

Fig. 14b
Figs. 17a,b,c

Fig. 17a

Fig. 17b

Fig. 17c
Figs. 18a, b, c

Fig. 18a

Fig. 18b

Fig. 18c
Fig. 20
FIG. 38A

FIG. 38B
INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER

INV. F24J2/54

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

F24J  H01L

Documentation searched other than minimum documentation: to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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X Further documents are listed in the continuation of Box C.  

Y See patent family annex.

* Special categories of cited documents:

*A* document defining the general state of the art which is not considered to be of particular relevance

*E* earlier document but published on or after the international filing date

*L* document which may throw doubts on priority claims(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

*O* document referring to an oral disclosure, use, exhibition or other means

*P* document published prior to the international filing date but later than the priority date claimed

Date of the actual completion of the international search

16 March 2010

Date of mailing of the international search report

14/07/2010

Name and mailing address of the ISA

European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3916

Authorized officer

Oliveira, Casimiro
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INTERNATIONAL SEARCH REPORT

Box No. II  Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
   because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
   because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
   because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III  Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

see additional sheet

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☑ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

   1-51, 57-59, 64-71

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.
This International Searching Authority found multiple (groups of) inventions in this international application, as follows:

1. claims: 1-51, 57-59, 64-71

Multi-element two- or three-axis pointing array, tracking system and means for concentrating and capturing the radiation collected thereby

1.1. claims: 1-36

Multi-element two- or three-axis pointing array of several direction-critical elements, means for positioning said several direction-critical elements

1.2. claims: 37-43

Tracking system for a multi-element pointing array

1.3. claims: 44-51

Optical structure for controlling and directing light for a multi-element pointing array

1.4. claims: 57-59, 64-71

Concentration of radiation on capturing surfaces by a multi-element pointing array

2. claims: 52-56

Multi-element two- or three-axis pointing array forming a directional lighting system

3. claims: 60-63

Multi-element two- or three-axis pointing array comprising a radiation trapping cavity.
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