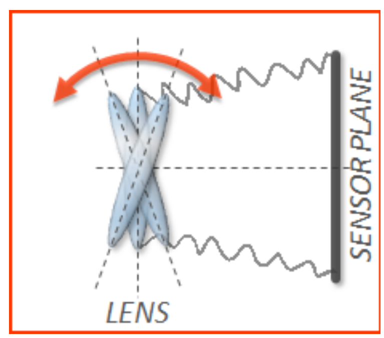
Lens swivel for all-in-focus image capture

Commercial Application
With the latest development of computational methods a new age in photography is taking place, enabling exploration in the 3D captured scene, even after it has been captured. While typical cameras have a limited depth of field (DOF), often causing blur and loss of image detail, new image refocusing techniques allow improvement (and interactive changing) the plane of focus and DOF of an image during or after the image capture. One way to (e.g. post-factum) refocus is to instant capture the entire light field by a plenoptic camera (4D data capture).[1] However, this leads to a significant reduction in image resolution. Other refocusing techniques use 'focal stack' approaches (3D data capture). 'Focal stack' is a set of images of the same scene captured at different focus settings and used to facilitate refocusing in real-time or by a post-processing. For this purpose, a 'sweep camera' physically sweeps its focal plane across a scene during the direct capture, directly recording focal stacks (unlike the light-field camera), hence preserving sensor spatial resolution and saving the computation power/rendering time. Alternative sweeping methods can even contain a dynamic scene captured within a finite time period and, therefore, include the motion within the scene. In a simpler way, captured focal stack can be used to blend in-focus (sharp) patches from individual images following registration and appropriate scaling or, alternatively, for post-refocusing.

While capturing an instant light field[1] is beneficial in some situations, capture within the duration of time can result in a unique processing/refocusing experience, such as simultaneous perception of the dynamic objects within the scene by a user, e.g. combined with the dynamic focusing. Focal sweep can be implemented in multiple ways. Since scene motion and camera-shake can lead to motion blur in the captured images, it is important to capture the entire focal stack in short time, typically by either translating the scene along the optical axis during image exposure, or by sweeping the image sensor relatively to the subject. For a given pixel size, frame rate, and f-number of the lens, the overall capture time and total image count are highly related to focal length and scene distance range.

Technical Description Summary
Indranil Sinharoy and his colleagues from Southern Methodist University proposed a method of creating an all-in-focus photography by processing focus stack images acquired as the lens is swiveled around a pivot point (an alternative to sensor-subject movement). In this case, the unique focal stack is created directly from planes-of-sharp-focus, while the camera angularly sweeps the object space.



The principal advantage of the method is the reduced number of images needed to assemble an all-in-focus image, especially in scenarios with infinitely large depth of the scene. Comparing to existing focal sweep techniques, this method requires a much smaller number of images (and simpler reconstruction procedure) for scene objects where the DOF varies from very close range to infinity. Selective focus, post-factum refocusing, and scene depth estimate are also possible by implementing the method.

[1] Lytro™ , https://www.lytro.com/

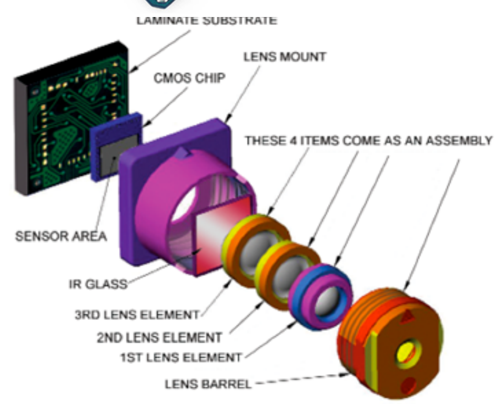
Competitive Advantage

Existing solutions

An auto-focusing (AF) camera uses an actuator to move one or more lenses along the optical axis, while an algorithm calculates a figure of merit for the image sharpness for that lens location. Moving the lens then changes the focus accordingly, and a new figure of merit is obtained. The conventional focal sweep functionality could be added to various existing cameras with minimal modifications (as simple as a firmware update). Auto-focus has become a standard feature in cameras across all categories, from cell phone cameras to professional SLRs. An image is typically captured after the camera adjusts its focus, either by moving the sensor (cell phone) or changing the relative distance between the optical components within a lens (SLR). In comparison, a focal stack is captured while the focal plane of the imaging system is swept through a predefined range. Since the inventors have not defined the specific market for the method, there are 2 possible scenarios that can be implemented for the method. Specifically, the angularly sweep focal stack capture can be implemented either with non-miniature lens systems or with miniature camera modules.

Miniature lenses

More than two billion miniature cameras are manufactured annually for the cell phone and tablet markets. Of these, about 40% use autofocus (AF). Moreover, phone cameras do a lot more processing by sophisticated software. Low-end cell-phone cameras employ fixed-focus lenses in combination with small sensor and virtual infinite depth of field, hence eliminating defocusing problems at the price of the low-quality image. However, recent more expensive phone models (iPhone 6, Samsung Galaxy 6+) do have moving lenses along with phase detection to assist in auto-focus (AF). The lenses are relatively wide, and the aperture is very small (somewhat hidden by the manufacturers under 'effective' focal length and aperture, taking into account a tiny sensor size). Such lenses require very little focusing since the distance of moving the lens into focus is very miniscule. In general, the amount of motion required to focus a lens is far less than the amount required for zooming.



Silicon MEMS actuators have superior (relatively to macro-components) mechanical and electrical characteristics on top of the advantage of modern manufacturing processes, making them highly suitable for next-generation miniature autofocus cameras. Such cameras provide greater autofocus speed, higher precision, dramatically reduced power consumption.[2,3] Modern software (faster algorithms) further accelerates camera-focusing features (e.g. fast face focus technique).

Non-miniature lenses

For non-miniature lenses (including interchangeable lenses for mirror-less and DLSR systems), using focusing motors is preferable for the focal stack capture. AFD Motors, Micromotor and USM (ring ultrasonic motors and the micro ultrasonic) motors are typical means for such lens systems focus control. The concept of the focus tilt (and pivoting) for such lenses is not new and has been implemented

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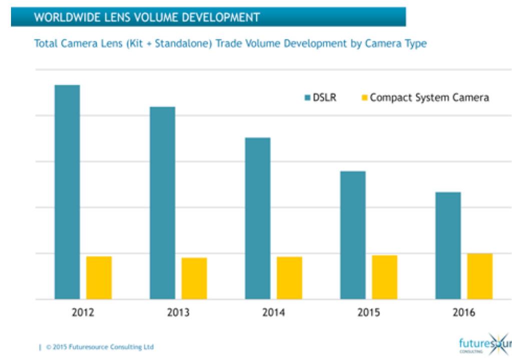
[2] http://www.digitaltrends.com/mobile/digitaloptics-lytro-like-mems-cam-hands-on/
[3] Image courtesy of iFixit.

elsewhere[4] (as has performance simulation[5]). Most of the focus sweep cameras, however, have been realized using off-the-shelf highly advanced AF lenses.[6]

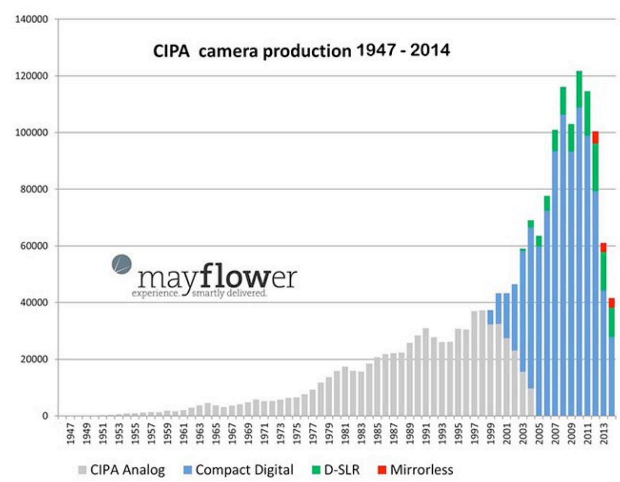
Market, Trends and Competitive Landscape

The global demand for total camera lens (camera kit + standalone lenses, no miniature camera modules) manufacturing was 22.2 million units in 2014 (an annual drop of 13%). The value performance for standalone lenses, however, fell by only 3% to \$3.9 billion. The average standalone lens prices grew by 4% to \$527.[7] Kit lens sales fell by 15% to 14.8 million units, while standalone lenses only fell by 8% to 7.5 million units.

Standalone lenses outpaced demand for kit lenses across most regions except the US, where DSLR kits have been heavily promoted. Standalone lenses are expected to continue outpacing kit lenses throughout the forecast. Worldwide DSLR standalone lens volumes fell by 9% in 2014 (year-on-year). Industry feedback suggests that users are less inclined to invest in a new DSLR system due to slowing product innovation and are more likely to enhance their existing system with new lenses. However, there was positive growth with the Compact System Camera (CSC) segment, with standalone lens volume growing by 12% versus 2013, expecting the CSC segment to continue growing out to 2018.



The photo specialists remain the largest consumer sector for standalone lenses. This sector benefited from the rising demand for higher value cameras and features in 2014, resulting in its share of standalone lens volume and value growing across most developed markets, particularly across Western Europe.



Demand for entry-level camera kit lenses declined 30% across most developed markets. Smartphone sales topped 1 billion in 2013 (1.2 billion in 2014), up 38% year over year, while digital camera shipments plummeted from around 98 million in 2012 to 63 million units in 2013, with the biggest losses coming among mid- and low-priced models[8]. The figure to the right shows that the camera market has been shrinking by double-digit figures each of the past few years since a huge spike in the 2000s. The biggest victim has been compact cameras, which are becoming redundant as smartphone camera quality continues to improve. It is unclear, however, how much of this drop can directly be attributed to the rise of the smartphone cameras.[9] DSLR and mirrorless cameras have

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[4] http://lensbaby.com
[5] http://lensbaby.com/usa/sim-e50.php
[6] http://www1.cs.columbia.edu/CAVE/projects/focal_sweep_camera/
[7] Futuresource Consulting report, 2015.
[8] By CIPA (Camera & Imaging Products Association).
[9] Heino Hilbig, Mayflower Concepts.

not been affected as much, but they are definitely not helping the overall trend for cameras in general. Total sales are roughly at levels they were a decade ago.

Miniature lenses market

Driven by recent advances in and demands for mobile technology, such as smart phones and tablet computers, as well as growth in medical device and automotive applications, camera module demand is growing. There were a few releases about upcoming chips and sensors for cell phones that will finally bring improved photo quality to the devices.[10] While phone pictures still are not good enough for camera enthusiasts, they are suitable for less demanding consumers, and it has started to sting manufacturers. Improved software, flashes, auto focus features, and even optical zoom could be hitting cell phones in the next few years, starting in the Asian and European markets. Lower-end camera makers will have to step up their game to convince customers that it is worth owning a separate device for taking photographs.

According to one report, the global camera module market was valued at US $12.0 billion in 2012 and is expected to reach $43.06 billion by 2019 (more than 1.5 billion units produced in 2013), growing at a compound annual growth rate (CAGR) of 19.7% between 2013 and 2019.[11] According to another report, the total camera modules market is expected to reach $36.95 billion by 2020, growing at a CAGR of 10.8% between 2015 and 2020.[12] This advancement is reflected to some core technologies in the camera modules market such as 3D depth sensing, infrared thermal technology, 4K pixels, ultra HD display technology, and panoramic technology.

The global camera modules market was valued at $19.21 billion in 2014 and is expected to grow at a CAGR of 10.8% between 2015 and 2020. Currently, the consumer electronics application holds a largest share. However, in order to reach their full potential and produce high-quality images that are also highly focused, they must be assembled with precision. To best approach the increasing challenges of the industry, the software and hardware aligning and assembling these cameras must work in unison to create a product that is assembled both accurately and efficiently. Software algorithms created to gather feedback from an active lens-to-sensor alignment process to adapt and improve camera performance for more efficient cycle times.

Development Directions

As reported by the inventors, the accuracy of the model has been initially verified through optical ray tracing software.[13] Using the new model, authors have also found the special conditions required for capturing images for all-in-focus imaging using lens swivel. Based on the disclosure provided, it is assumed that the current state of the technology development can be best described as in the concept phase with the physical principle demonstrated. No actual angularly sweep focal stack capture (e.g. lens system, motion control, software /electronics) have been considered. At this stage, focal sweep camera developers form a niche-market with some ideas that would probably be adopted by larger vendors.

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[10] http://www.steves-digicams.com/news/are_cell_phones_hurting_the_digital_camera_market.html
[11] Transparency Market Research report, "Global Camera Module Market - Industry Analysis, Size, Share, Growth, Trends, and Forecast 2013 – 2019".
[12] MarketsAndMarkets report, "Camera Modules Market by Component (Image Sensor, Lens Module), Process (Flip-Chip), Pixel, Application (Consumer Electronics, Security & Surveillance, Automotive, Aerospace & Defense, Industrial), and Geography - Global Forecast to 2020", October 2015.
[13] https://en.wikipedia.org/wiki/List_of_ray_tracing_software

Practically demonstrated proof of concept is an important next step in development. Furthermore, since pricing, mobility and reliability play a vital role in determining the competitive strength of the invention, the authors should address:

- Application of the method to camera modules (along with the standalone lens systems), if possible.
- Direct comparison with the existing focusing lens systems, demonstrating the advantage of the potential reduction in image numbers needed for DOF extension/optimization (for the same scene and image parameters, if possible).

Commercialization Suitability

The focal sweep imaging systems reported in the literature are typically used in small focal length lenses, since it is challenging to move a sensor by required distances at frequencies above a few Hz, which is limited by the actuator performance and induced sensor vibration (image quality deterioration).
The use of deformable optics have been reported elsewhere[14] to address such problems, since the fast response-time of deformable optics enables periodic focal sweep at higher frequencies for larger focal lengths. As an example, the invention could offer focal sweep imaging system as a more effective alternative to deformable optics. Moreover, if implemented effectively, the proposed angularly sweep focal stack method can also provide near infinite depth-of-field with fewer images captured (and potentially simpler image reconstruction procedure/post-focusing possibilities).

However, proof of concept of the new, potentially more efficient lens swivel system has to be practically demonstrated to promote an adoption of the technology. The realization of precisely-controlled angular-sweep lens system is very complex, and it is not clear the advantage of a potentially fewer images within the focal stack is justifiable in comparison with the well-advanced axial AF solutions widely available to use in conventional focus sweep cameras. Moreover, the actual implementation could be even more cumbersome, since the invention is mostly applicable to 'symmetric' lenses (with pupil-magnification (P) equals one). As explained by the inventors, if P is not equal to 1 (which is true for the most off-the-self lenses) the image alignment becomes non-trivial. (Very generally, telephoto lenses have a P<1, while wide angle lenses generally have a P>1.) P isn't necessarily a strict function of focal length. The proposed method is probably not compatible with the zoom feature of the typical lens system.

While feasible, it is not clear how the proposed angular-sweep lens technique can be realized/ implemented in modern miniature camera modules without major hardware redesign/modification. Moreover, having aforementioned efficient focusing modules (and software) in place, it is not obvious whether the proposed lens pivoting method would justify such modification in terms of improved depth of focus. Traditionally, the lens barrel of a camera is manufactured with threads so that it could be attached to the sensor using a screw-in method that allows for alignment in one degree of freedom, adjusting the distance of the lens from the sensor. This method often fails in small-scale high-megapixel camera modules; that is, if the lens or sensor is embedded at an angle, and only the center of the image is focused, the edges of the image will be noticeably out of focus. Realization of the angular degree of freedom would require further modification.

[14] D. Miau et. al., "Focal Sweep Videography with Deformable Optics", Conference: 2013 IEEE International Conference on Computational Photography (ICCP), 2013.

Potential Partners

The key vendors in the global lenses/ camera modules market/ research include:

Company Name and Focus
Canon U.S.A., Inc. One Canon Park Melville, NY 11747
Sony Corporation 1-7-1 Konan Minato-ku, Tokyo, 108-0075 Japan
Toshiba America Electronic Components 15015 Avenue of Science # 110, San Diego, CA 92128
LG Innotek 2540 N 1st St # 400, San Jose, CA 95131 lginnotek.com **LG Technology Center of America (LGTCA)**
Fujifilm Corporation 26-30, Nishiazabu 2-chome, Minato-ku, Tokyo 106-8620, Japan **Fujifilm North America** 2121 N California Blvd, Walnut Creek, CA 94596

Other major players include: Nikon, Panasonic Corporation, SHARP Corporation, Cowell, Foxconn Technology Group, Lite-On, Omnivision, Partron, SEMCO, Sunny Optical Technology, DigitalOptics Corporation, Chicony Electronics, STMicroelectronics, AAC Technologies Holdings, AzureWave Technologies, Bison Electronics, CammSys Corporation, Lite-On Technology Corporation, STMicroelectronics NV, Sunny Optical Technology