A Smart Fast Camera

Roberto Ragazzoni[*a,b], Carmelo Arcidiacono[c], Emiliano Diolaiti[d],
Jacopo Farinato[a], Anna Moore[a], Roberto Soci[b]

[a]INAF-Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, I-50125 Firenze, Italy;
[b]Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany;
[c]Dip. Astronomia e Scienza dello Spazio, Univ. Firenze, L.go E. Fermi 5, I-50125, Firenze Italy;
[d]INAF- Osservatorio Astrofisico di Bologna, Via Ranzani 1, I-40127, Italy

ABSTRACT

It is generally believed that very fast cameras imaging large Fields of View translate into huge optomechanics and mosaics of very large contiguous CCDs. It has already been suggested that seeing limited imaging cameras for telescopes whose diameters are larger than 20m are considered virtually impossible for a reasonable cost. We show here that, using existing technology and at a moderate price, one can build a Smart Fast Camera, a device that placed on aberrated Field of View, including those of slow focal ratios, is able to provide imaging at an equivalent focal ratio as low as F/1, with a size that is identical to the large focal ratio focal plane size.

The design allows for easy correction of aberrations over the Field of View. It has low weight and size with respect to any focal reducer or prime focus station of the same performance. It can be applied to existing 8m-class telescopes to provide a wide field fast focal plane or to achieve seeing-limited imaging on Extremely Large Telescopes. As it offers inherently fast read-out in a massive parallel mode, the SFC can be used as a pupil or focal plane camera for pupil-plane or Shack-Hartmann wavefront sensing for 30-100m class telescopes.

Keywords: Wide-field camera, seeing limited, lenslet array, wavefront sensing, Extremely Large Telescope, Smart Focal Plane

1. INTRODUCTION

Wide Field imaging for apertures in the class of 8m telescopes requires a special effort. On existing telescopes the largest available Field of View (FoV hereafter) at the Second focus station (such as Nasmyth) is of the order of 10-20 arcmin[1] while a larger FoV can be obtained through Prime Focus correctors[2]. In both cases a wide-field corrector is required that represents a substantial part of the cost of the instrument, in addition to being a large, heavy and complex device often with optical elements close to the edge of feasibility of current industrial capabilities. In the case of wide-field imaging at the Nasmyth foci the corresponding camera required is also large and complex, especially if multi-object spectroscopy is provided.

In such instruments light is finally detected by a large array of buttable and expensive CCDs with a read-time, even using state-of-the-art controllers that lies in the range of several seconds. Optics as heavy as a hundred Kilograms, of size marginally under a meter requiring years for procurement of blanks and polishing, are common. The proposed next generation of prime focus correctors are even more ambitious[3,4].

The difficulty in exploiting a wide FoV on 8-m class telescopes leads to a number of projects with dedicated telescopes for large surveys. These range from an array of small telescopes[5] (where the above mentioned problems are reduced by using a number of identical smaller focal stations) to specifically designed larger telescopes[6,7]. As the latter cannot be used for general purpose but, instead, for a specific survey-type science, they do not satisfy the entire astronomical community and, in reality, are made possible only after the successful deployment of a number of more conventional, multi-purpose, 8m-class telescopes (like VISTA in the VLT case, for example).

We introduce a novel design for wide FoV imaging that offers many advantages over the above mentioned approaches. The design, referred to as the Smart Fast Camera (SFC) henceforth, can be placed in the more convenient slower focal length stations rather than the fast prime focus, it is conveniently modular and allows for extremely fast detector readout. It can be made significantly cheaper than existing alternatives, although it is noted this is probably not the most appealing feature of such a concept.

*Offprint request to ragazzoni@arcetri.astro.it

Ground-based Instrumentation for Astronomy, edited by
Alan F. M. Moorwood, Masanori Iye, Proceedings of SPIE Vol. 5492
(SPIE, Bellingham, WA, 2004) · 0277-786X/04/$15 · doi: 10.1117/12.552035

Further possible applications are also discussed.

2. CONCEPT

It is interesting to note that the concept we describe, although novel for wide-field imaging, explores more in detail the ideas of field spectroscopy, such as TIGER[8], SAURON[9], Content[10], and the technique to achieve multiple pupil reimaging to reduce thermal emission[11]. In this respect the name we have given to the camera is taken from the terminology used in Smart Focal Arrays[12].

We recall here the conditions a fast camera design has to meet and which are the traditional consequences of a conventional on-axis centered optical layout. A fast camera design (including wide-field corrector) must provide: a large FoV (that physically translates into large optics); a fast focal ratio for proper sampling with currently available pixel sizes (that translates into the choice of a Prime Focus station or to a Focal Reducer in a second focal station); the capability to compensate for relatively large FoV-dependent aberrations (that leads to the adoption of a number of optical elements to control simultaneously the wavefront distortions, often requiring complex aspheric surfaces involved in the optical design) and; a physically large detector area (that translates into the adoption of a certain number of large format buttable CCDs).

In actuality, most of the issues listed above are simply a consequence of the first: by reducing the FoV requirement (something that of course sounds nonsense for a wide FoV camera) all the technical drawbacks cited above are substantially reduced if not eradicated altogether. In particular, a focal reducer for a small FoV can be achieved with simple optics and, as soon as a pupil plane is made available, this can be used to compensate aberrations that are expected to vary slowly within such a small FoV. As shown in Fig. 1 the basic principle of the SFC is to replicate such a relatively small FoV focal reducer on a bi-dimensional matrix, eventually allowing one to cover a much larger FoV. The replicas are identical, other than for the aberration compensation plates that depend upon the position in the telescope FoV.

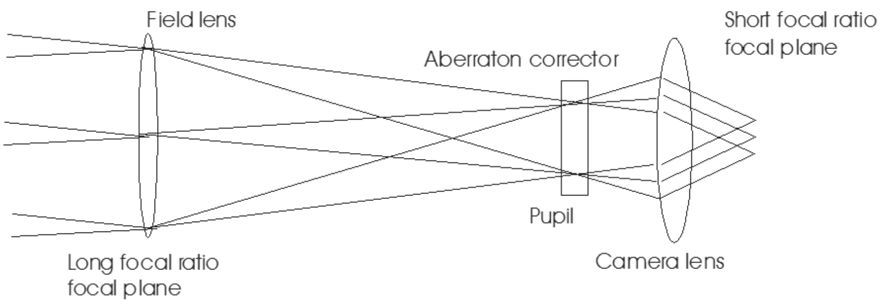

Fig. 1. Schematics of a single focal reducer of the SFC. The pupil plane can now house an aberration compensator. The optics placed off-axis are “tuned” to the average aberration encountered in the focal reducer FoV. Only residuals due to the variations of aberration over the mini-FoV are recorded in the focal plane. Once the FoV covered by such a focal reducer is small, the optical design can be as simple as just two or three lenses.

One can now cover the FoV with an array of almost identical lenslet focal reducers, similar to that shown in Fig. 2. The lenslet focal reducers differ only in the type of pupil plane aberration corrector chosen that is a function of focal plane radial position only.

If one allows the focal surface to be curved substantial simplification of the lenslet optics are possible. It is felt this curvature can be accommodated by the printed circuit board onto which the array of CCDs is connected.

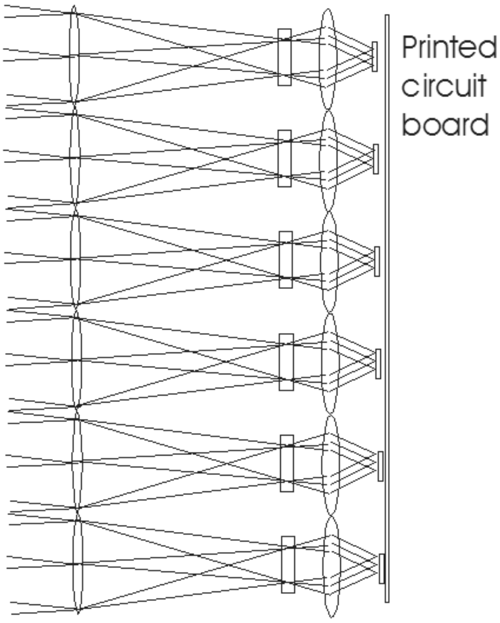

Fig. 2. Replication of a focal reducer as depicted in Fig.1 will allow coverage of a much larger FoV. The FoV dependent aberrations are corrected by using different pupil plane corrector plates.

A schematic of the SFC concept is shown in Fig. 3. The image, with large plate-scale (hence physically large) formed in the focal plane is segmented by the array of lenslets[13], each ~1 arcmin square. An array of aberration correctors are placed in the pupil plane, each correcting the approximately constant aberrations found across the FoV of each lenslet system. Finally an array of camera lenses produces an array of images detected by the CCDs, with a much more user-friendly plate-scale.

Whenever the aberration on the long focal plane is large, objects imaged on the edges between two adjacent lenslets will be shared between the corresponding detectors. Therefore it is suggested the size of the latter element should be enlarged with respect to the nominal one by the largest spot aberration so that no light loss occurs, other than losses due to the imperfections of the lenslet edges. This will result in a small overlap of adjacent parts of the FoV.

3. A MODULAR APPROACH

The SFC design summarized has the great advantage that it lends itself to a modular design approach. If we assume, for now, a base element (or module) of a 4 × 4 lenslet array, covering roughly 4 square arcmin of sky as shown on the left-hand side of Fig. 4, one can cover a physically large focal station with identical modules. Each module is in essence a small-scale instrument with corresponding sky coverage and read-out time. Therefore the performance of the SFC as a whole is limited only by the performance of these individual, simple modules. This feature has implications on the ease of manufacture, optical alignment, imaging performance and read-out time. One can imagine a 20 arcmin FoV image taken by an 8m-class telescope downloaded in the time it takes to read one CCD.

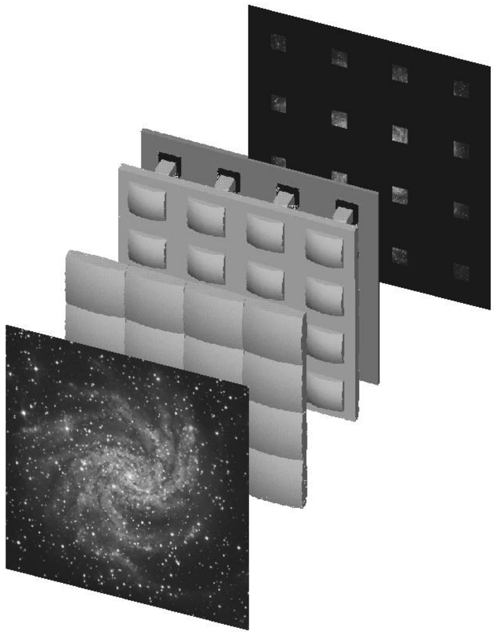

Fig. 3. A pictorial description of a SFC. The image with a relatively large plate-scale is projected onto the lenslet array whose elements are field lens of the single focal reducers, and portions of the images are then imaged with a smaller plate-scale onto a number of small detectors.

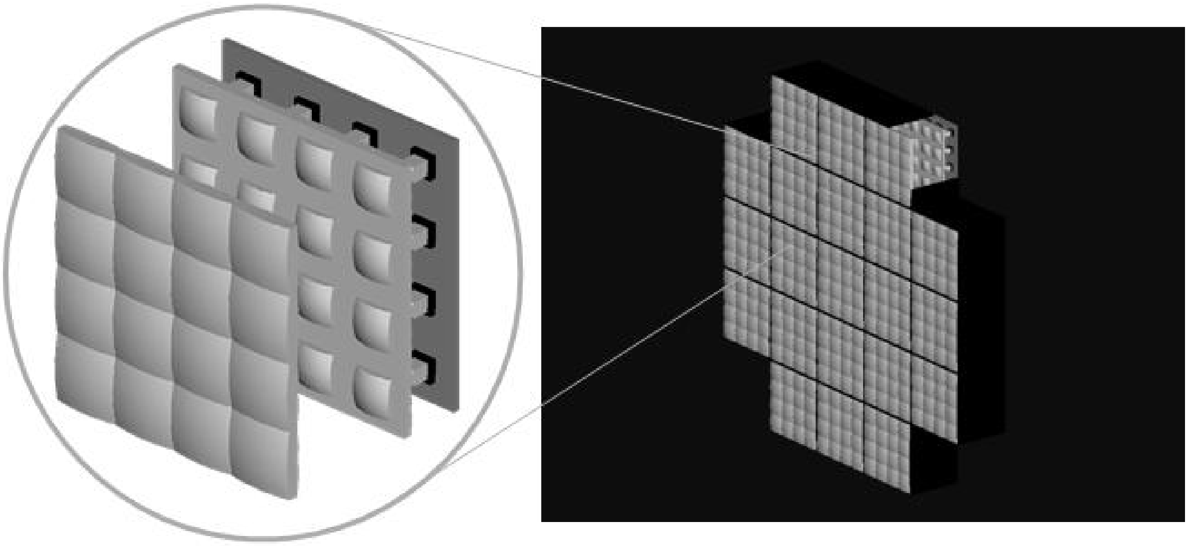

Fig. 4. The modular approach to the smart fast camera concept. A physically large FoV can be populated with virtually identical modules.

3.1. Filters

It is possible that fixed large filters can be inserted in each module (in between the lenslet array and pupil plane). This would allow for filter interchange once per day rather than between observations. For a survey orientated instrument this

may be viable. An interchangeable filter for each CCD is felt, for now, too difficult to achieve in practice for the gains provided.
A variation of the fixed format filter is shown in Fig. 5, where the fixed filter for each module is composed of an array of single filter types (4 are shown in the figure) where each of the individual filters are aligned with a lenslet. This simple arrangement provides multi-colour imaging during a single observation.

4. PROS AND CONS OF THE SFC CONCEPT

The advantages of the SFC concept are as follows. The instrument can be located at Cassegrain or Nasmyth stations that are more accessible and do not, in general, require complicated top end changes. The design is much smaller and lighter than obvious competitors requiring large wide-field correctors. The design is modular in nature that allows for mass production, and is therefore cheaper to produce. Another benefit of the modular nature is that the performance of the SFC as a whole is only limited by the performance of a single module. For example, one only has to read a lot of small CCDs rather than a large buttable CCD array allowing for parallel fast readout. One can now consider a video-rate 8m sky survey or high speed celestial cinematography as options for new parameter space. Frame transfer CCDs are doable and therefore one can avoid the need for a shutter.
The disadvantages of such a system are as follows. The sub-frames will be always slightly non-in-grid and will require an extra level of data reduction compared to continuous coverage of the focal plane. An issue regarding filter interchange was already discussed in the previous section. Cost effectiveness can be achieved, most likely, only for large FoV. A further issue concerns the cooling of the detectors. If cooling to -40C is required only, for example for surveys requiring short duration exposures only, cooling through a Peltier system can most easily take advantage of the modular approach. If the dark current needs to be severely reduced, as required for longer exposure images, the CCDs must be placed inside a cryogenic chamber. For the cooling of multiple CCDs it is worth noting that cryogenic vacuum chambers can be divided into several subunits, where each subunit matches a single module, but issues regarding complexity and space may become important. The most obvious approach is to have one cryogenic vessel for each module but alternative configurations are currently under investigation.

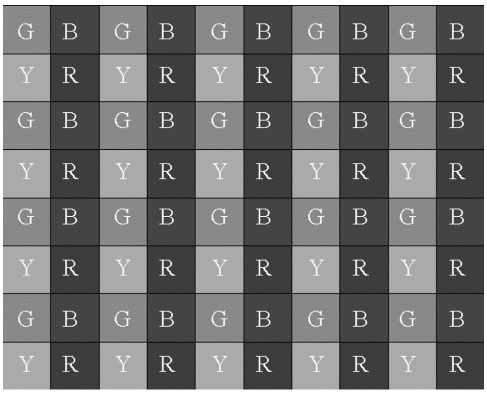

Fig. 5. Schematic of a possible fixed format filter scheme for the smart fast camera.

The following should also be noted. A trade-off is required to establish the optimum size of the subapertures. This is not only dependent on optomechanical issues but also on, and maybe most importantly, the dominant science case. A very small supaperture requires a lot of small (256x256 or 512x512) CCDs but the corresponding optics are easy and cheap. Larger subapertures allow for a smaller overall number of medium size chips (1kx1k, 2kx2k) but the optics can be more demanding (most likely more than 2 lenslets). Optimisation in this area is on-going.

5. APPLICATIONS

The SFC design is not only limited to a wide-field camera for 8m class telescopes. Given the modular nature of the design it could be easily extended to fill the focal surface of an ELT, providing a wide-field seeing limited imaging facility previously thought unfeasible due to the very large physical diameters of the focal stations of such telescopes.

The SFC concept can also be applied to wavefront sensor design for ELTs[14]. In addition, and one of the most exciting applications, is in the area of multi-object spectroscopy, specifically in the area of large-scale spectroscopic surveys[15,16]. In such a concept (nicknamed the SFS or Smart Fast Spectrograph) the detector surface is replaced with an array of multi-fibre positioners, at least one positioner per lenslet. Each fibre is positioned on a target in the lenslet FoV and the light is conveyed to a spectrograph located in a thermally and mechanically stable environment. The fibre positioners could be simple piezoelectric devices, with more complex versions already common use is this field[17]. The concept offers exciting prospects for 8m large-scale spectroscopic surveys and beyond, where a large FoV and spectra numbers (up to millions are required for certain cosmological science[18]) are critical. The feasibility of the SFS is currently being investigated.

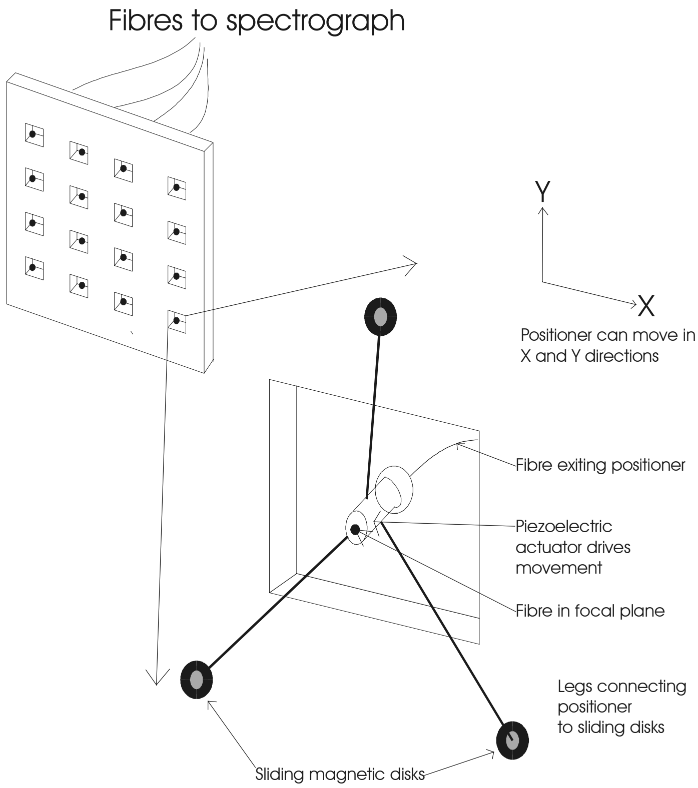

Fig. 6. A schematic of the positioner of a single module of a Smart Fast Spectrograph based on the SFC design. Here the detector array of the SFC is replaced by a plate containing optical fibre positioners. In this drawing there is one fibre positioned in the FoV of each lenslet. The fibre is positioned with the required accuracy using a piezoelectric driven inertial device, based on existing technology.

6. CONCLUSIONS AND FURTHER WORK

Presented is a novel design for a wide-field camera independent of telescope focal station. The design corrects for wide-field aberrations by segmenting the focal plane into manageable fields, over which the aberrations are relatively constant. This has the virtue of requiring very simple optics to produce the seeing-limited imaging performance required from a wide-field imager of this FoV (10 arcmin to several degrees).

A preliminary design study has commenced already to show the feasibility of 2-3deg FoV camera for LBT. Due to CCD-controller cost we are initially oriented towards 'large' subapertures. It is noted that the SFC design is not limited to imaging applications only. Indeed, for several reasons the concept is ideally suited to multi-object spectroscopy using optical fibres, or 2D spectroscopy using integral field units (IFUs). We are therefore considering a double instrument system of one SFC stationed at a single Nasmyth focus acting as an imager and, at the twin mirror focus, placing a SFS (Smart Fast Spectrograph).

7. ACKNOWLEDGEMENTS

We thank greatly Jim Beletic for guidance in the area of CCD design for the SFC. Thanks are due to the crew at the Copenhagen's McDonald restaurant where the idea was born into creation.

REFERENCES

1. L. Pasquini et al, "Installation and first results of FLAMES, the VLT multifibre facility", *Proc. SPIE*, **Vol. 4841**, pp. 1682-1693, 2003.
2. Y. Komiyama et al, "Suprime-Cam: Subaru prime focus camera", *Proc. SPIE*, **Vol. 4841**, pp. 152-159, 2003.
3. Y. Komiyama et al, "Subaru next generation wide-field camera: HyperSuprime", *Proc. SPIE*, **Vol. 5492**, in press, 2004.
4. M. Liang et al, "Wide field corrector with ADC compensator and image stabilizer for f/1.7 Gemini Telescope prime focus", *Proc. SPIE*, **Vol. 5492**, in press, 2004.
5. M. Kaiser et al, "Pan-STARRS: A Large Synoptic Survey Telescope Array", *AAS*, **Vol. 34**, p.1304, 2002.
6. J. R. P. Angel et al, "LSST Optical Design", *AAS*, **Vol. 33**, p.1462, 2001.
7. L. G. Seppala, "Improved optical design for the Large Synoptic Survey Telescope (LSST)", *Proc. SPIE,* **Vol. 4836**, pp. 111-118, 2002.
8. J. E. Larkin et al, "OSIRIS: infrared integral field spectrograph for the Keck adaptive optics system", *Proc. SPIE*, **Vol. 4841**, pp. 1600-1610, 2003.
9. R. G. Bower, "The SAURON Deep Field: Investigating the Diffuse Lyman-alpha Halo of Blob1 in SSA 22" , *ING Newsl*., issue no. **7**, pp. 5-8, 2003.
10. R. Content & T. Shanks, "NG2dF - A Next Generation 2-Degree Field Instrument for the AAT", *Submitted to AAO Users' Committee*, July 2002.
11. G. Monnet, Pri. Comm.
12. A. P. Russell et al, "Instruments for a European ELT: 1. the challenges of designing instruments for 30- to 100-m telescopes", *Proc. SPIE*, **Vol. 5492**, in press, 2004.
13. V. Shaoulov, J. P. Rolland, "Design and assessment of microlenslet-array relay optics", *Applied Optics*, **Vol. 42**, No 34, Dec 2003.
14. R. Ragazzoni et al, "Wavefront sensing on 100m scale", *Proc. SPIE*, **Vol. 5490**, in press, 2004.
15. J. Lewis et al, "The Anglo-Australian Observatory 2df facility", *MNRAS*, **Vol. 333**, pp.279-299, 2002.
16. T. Maihara et al, "Fiber multi-object spectrograph (FMOS) for the Subaru Telescope", *Proc. SPIE*, **Vol. 4008**, p. 1111-1118, 2000.
17. A. Moore et al, "Spine development for the Echidna fiber positioner", *Proc. SPIE*, **Vol. 4841**, pp. 1429-1439, 2003.
18. M. Colless et al, "Large Scale Structure from the 2dF Galaxy Redshift Survey", *AAS*, **Vol. 32**, p.1562, 2000.