Sharp imaging of Multiple object points: How and Why

P. Benítez\textsuperscript{1,2}, J.C. Miñano\textsuperscript{1,2}, M. Nikolic\textsuperscript{1}, L. Jiayao\textsuperscript{1}, J.M. Infante\textsuperscript{1}, F. Duerr\textsuperscript{3}

\textsuperscript{1}UPM, Spain \textsuperscript{2}LPI, USA \textsuperscript{3}VUB, Belgium
Abstract:

• Is it possible to sharply image M object points with N surfaces when N < M?

• Under what conditions?

• Why is it interesting for optimization?

• What is the role of the SMS method?

Answers will be given!
SMS method

Usually presented as a method to couple N wavefront pairs with N surfaces

**SMS 2D**
Up to 4 aspheres

J.C. Miñano et al., Optics Express, Volume 17, 2009

**SMS 3D**
Up to 2 free-forms

P. Benítez et al., Optical Engineering, 2003
However, recent findings seem contradictory.
Object versus Pupil discretization

- Object discretization

- Pupil discretization
Index

• Let’s start simple
• Facing the general case
• Application to optimization
• Conclusions
Early work

Cartesian ovals

These are 2D and 3D solutions

R. Descartes, "Géométrie", Leyden (1637)
On the problem of ideal flux concentrators

W. T. Welford
Blackett Laboratory, Imperial College, London SW7 2BZ, United Kingdom

R. Winston
Enrico Fermi Institute and Department of Physics, University of Chicago, Chicago, Illinois 60637
(Received 28 September 1977)

one of these for rays incident above the axis and the other for rays incident below the axis, and this is impossible. Thus in general it is not possible to correct a system with a finite number of surfaces for meridian rays to one off-axis object point, much less for skew rays. There are well-known exceptions to this, namely, systems of spherical symmetry such
On the problem of ideal flux concentrators: Addendum

W. T. Welford  
Blackett Laboratory, Imperial College, London SW7 2BZ, United Kingdom

R. Winston  
Enrico Fermi Institute and Department of Physics, University of Chicago, Chicago, Illinois 60637  
(Received 13 September 1978; revised 3 November 1978)

and so on. But we have only a finite number \( n \) of surfaces available, so that only \( n - 1 \) one-dimensional fans of rays can come to a point focus, not the full two-dimensional array in the pupil.

(1978)
First SMS designs

In 2D

In 3D

Curve D


P. Benítez, R. Mohedano, J.C. Miñano, SPIE Vol. 3781, 1999
First SMS designs

In 2D

\[ \text{v}_1 \]
\[ \text{v}_2 \]

\[ \text{D} \quad \text{D}' \]

\[ \text{A}_1 \quad \text{A}_2 \]

J.C. Miñano, J.C. Glez,
Appl. Opt. 31 (16), 1992

In 3D

P. Benítez, R. Mohedano, J.C. Miñano,
SPIE Vol. 3781, 1999
Convergence point
There are no degrees of freedom (analytic solution is unique)

Seed patch is not free!

Similarities

- All surfaces are at the aperture stop
- Both are unique solutions
- Number of object points = Number of surfaces
One surface, two object points
One surface, two object points
Early works

On the problem of ideal flux concentrators

W. T. Welford
Blackett Laboratory, Imperial College, London SW7 2BZ, United Kingdom

R. Winston
Enrico Fermi Institute and Department of Physics, University of Chicago, Chicago, Illinois 60637
(Received 28 September 1977)

A clue to another solution: if we have a surface in the system so placed that all the rays meet it on one side only of the axis, i.e., very remote from the aperture stop in ordinary lens design language, then this surface does not have to satisfy contradictory conditions and the edge-ray condition can be satisfied.

(1977)
Comparison

- Surfaces = beam print
- Two refractions

- Surface = 2 x beam print
- Single refraction

In both cases solutions are unique
Both cases can be also seen as two surfaces sharing one edge
Index

• Let’s start simple
• Facing the general case
• Application to optimization
• Conclusions
Increasing parallelism

Free patch
Increasing paralelism
Transition from two to three object points

Unique solution

Free patch

Unique solution
Increasing parallelism

Cartesian ovals

One surface, 10 object points

RMS diameter (arc min)

Incidence angle (degs)

One surface, 10 object points

RMS diameter (arc min)

Also in 3D
Series-parallel combinations

SMS thicker lenses do not have convergence points

Seed patch is not free

Seed patch is "nearly" free!!


Two surfaces, three object points

Convergence point

$v_1$

$v_2$

$v_3$

The two off-axis bundles cover the second surface exactly $\rightarrow$ Surface = 2 x beam print

Unique analytic solution exits

Two surfaces, three object points

Unique analytic solution exits

Transition from two to three object points

Unique solution

Free patch

Two object points

Three object points

Unique solution
Transition from two to three object points

Unique solution
Free patch
Unique solution

Two object points
Three object points
General rule of thumb

\[ \text{Number of object points} \leq \sum E \left( \frac{\text{Extension of surface}}{\text{Extension of beam print}} \right) \]

Number of object points (2D) \( \approx 2 + 2 + 1 + 2 = 7 \)
General rule of thumb

Number of object points ≤ \[\sum \frac{\text{Extension of surface}}{\text{Extension of beam print}}\]

Number of object points (3D; round field) \(\approx 2^2 + 2^2 + 1^2 + 2^2 = 13\)
Example

First design: 6 surfaces, 6 object points

$1+1+1+1+2+2 = 8$

Jose Infante, PhD dissertation, October 2013
Example

Improved design: 6 surfaces, 7 object points

\[1+1+1+1+2+2 = 8\]

Still improvable!
8 zeros should be achievable!
Index

• Let’s start simple
• Facing the general case
• Application to optimization
• Conclusions
SMS and optimization combination

When maximizing the object points to sharp image, we try to exhaust the degrees of freedom of aspherics and freeforms.

We conjecture that maximal SMS designs are close to a good solution (local minimum)
SMS optimization strategies

1. SMS surface can be combined with standard surfaces.

2. The free-parameters of the SMS (vertices positions, free patches, wavefronts) can be optimised.

3. An SMS design can be used as a good starting point for a standard optimization
Example: Imaging with high aspect ratio


Imaging with high aspect ratio

SMS 3D lens

SMS 3D lens + optimization

Imaging with high aspect ratio

Optimised rotational lens

RMS < 11 µm

SMS lens + optimization

RMS < 6 µm

Index

• Let’s start simple
• Facing the general case
• Application to optimization
• Conclusions
Conclusions

• Is it possible to sharply image M object points with N surfaces when N < M? Yes!

• Under what conditions? When surfaces are not at the aperture stop.

• Why is it interesting for optimization? You have a good starting point.

• What is the role of the SMS method? Provides a direct algorithm to the solution.
Acknowledgments

The Universidad Politécnica de Madrid (UPM) thanks:

- Synopsys for the academic licence for Code V
- LPI for their support under their Associated Entity Agreement

Thank you!