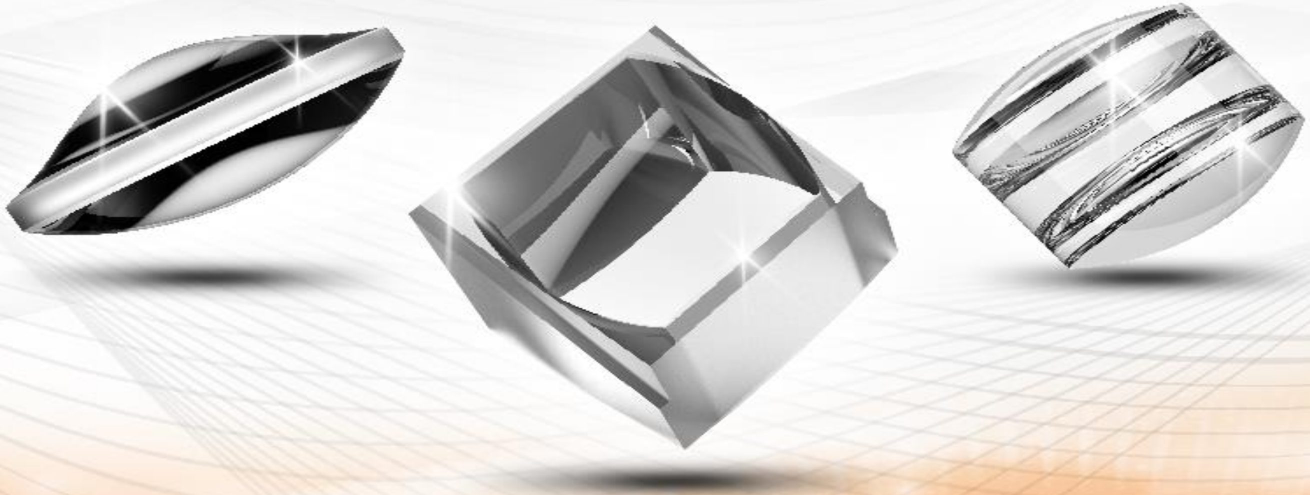
SPO | BEYOND THE BOUNDARIES OF OPTICAL SYMMETRY

FREEFORM optics design & manufacturing

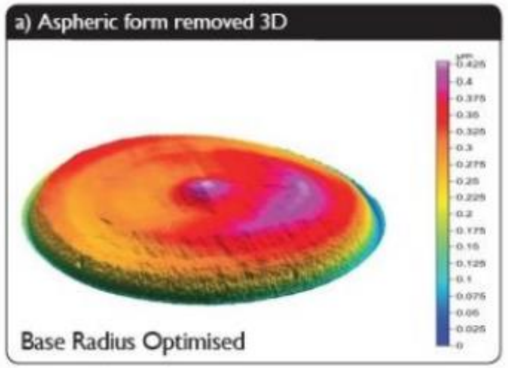


19.4.23

Nimrod Nissim

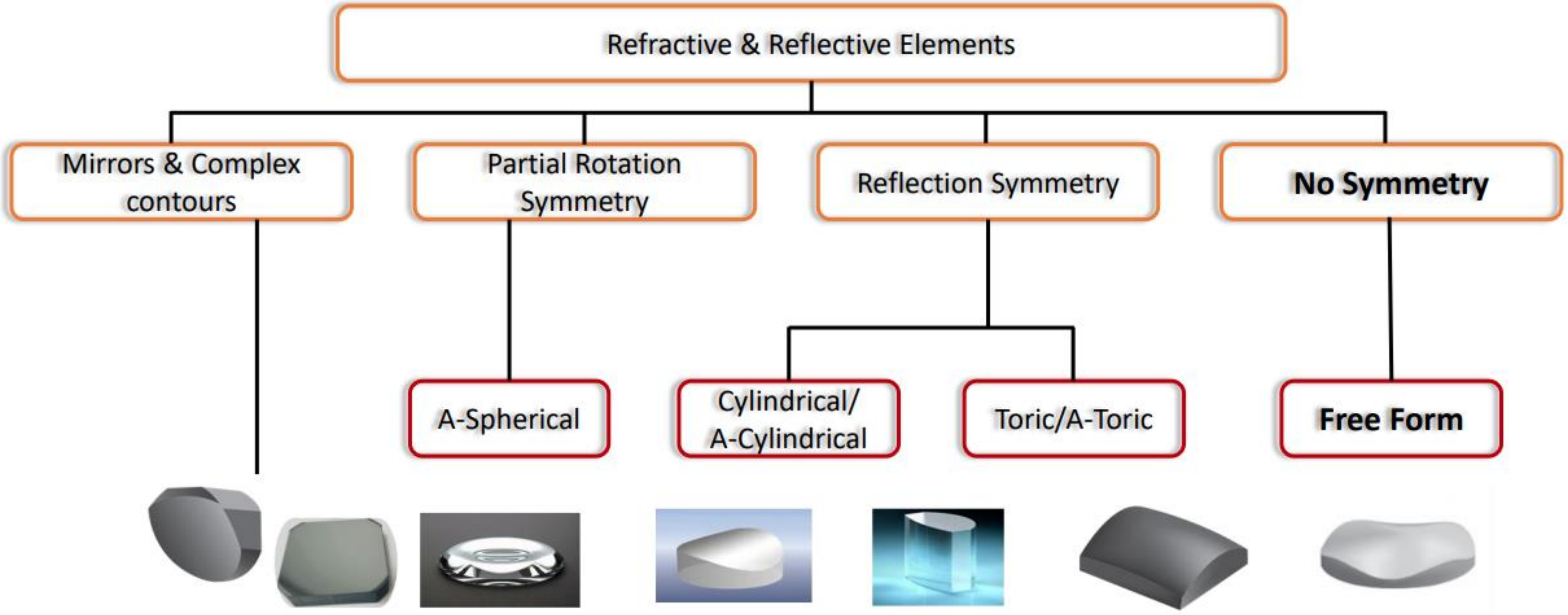
Capabilities needed for FF optics

Advanced optical-design & Production capabilities

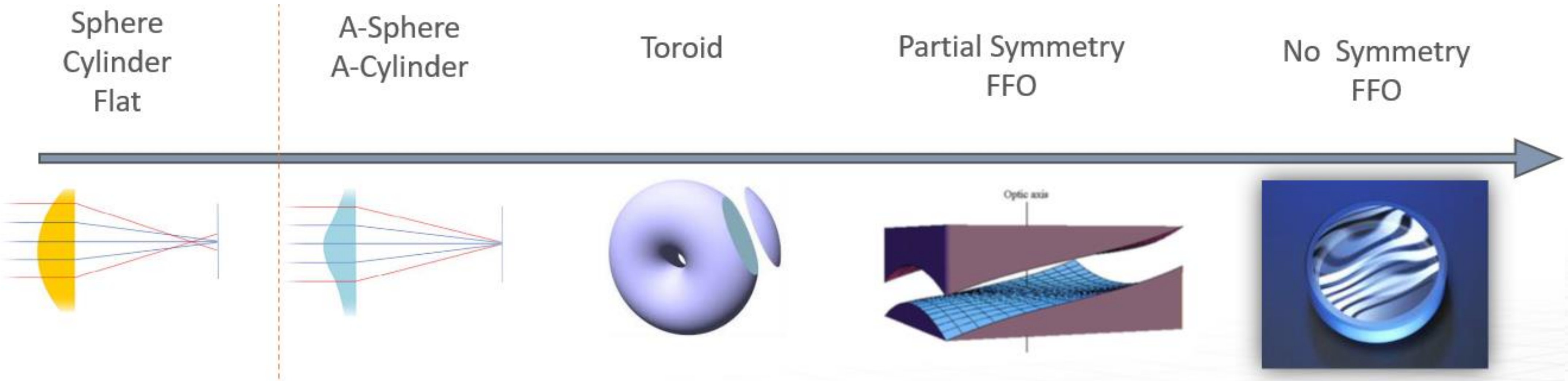


- CNC Optical Surfacing
- Metrology
- Coating
- Optical Cementing
- Optical Design

The complexity of optic components



The complexity of optic components



A-spheric & FF surfaces

Abbe 1902

$$z(r) = \frac{r^2}{R\left(1+\sqrt{1-(1+\kappa)\frac{r^2}{R^2}}\right)} + \alpha_4 r^4 + \alpha_6 r^6 + \cdots,$$

Zernike in 1934

$$Z_j(\rho,\phi) = Z_n^m(\rho,\phi)$$

$$= \begin{cases} \sqrt{n+1}R_n^0(\rho), & m = 0 \\ \sqrt{2(n+1)}R_n^m(\rho)\cos m\phi, & m \neq 0\ (\text{even}) \\ \sqrt{2(n+1)}R_n^m(\rho)\sin m\phi, & m \neq 0\ (\text{odd}) \end{cases},$$

$$R_n^m(\rho) = \sum_{k=0}^{(n-m)/2} \frac{(-1)^k (n-k)!}{k!\left(\frac{n+m}{2}-k\right)!\left(\frac{n-m}{2}-k\right)!}\rho^{n-2k}$$

Radial Function

Aspheric- Perturbed Conical Polynomials

Power series with conic section base Z(r)
Coordinates: Z; r
K= Conic constant
R=vertex radius
Rotational symmetry

Zernike Polynomials

Power series of 3D surface Z(ρ,ϕ)
Coordinates: Z; ρ; ϕ
n- Radial order
m- Azimuthal
Defined over circular aperture
Orthogonal Polynomials

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A-spheric & FF surfaces

Forbes 2012

$$f(\rho,\theta)=\frac{c\rho^2}{1+\sqrt{1-c^2\rho^2}}+\frac{1}{\sqrt{1-c^2\rho^2}}u^2\left(1-u^2\right)\sum_{n=0}^{N}a_n^0Q_n^0\left(u^2\right)$$
$$+\frac{1}{\sqrt{1-c^2\rho^2}}\sum_{m=1}^{M}u^m\sum_{n=0}^{N}\left[a_n^m\cos(m\theta)+b_n^m\sin(m\theta)\right]Q_n^m\left(u^2\right),$$

A “good” polynomial should fulfill some basic characteristics:

- Orthogonal
- Continuous Derivatives
- Better resistant to “ill conditioning”

Gradient-orthogonal Q-polynomials

Coordinates: f; ρ; ϕ

$u = \rho/\rho_{max}$

ρmax- Aperture radius

c- Curvature of best fit sphere

m,n – order indices

Describes the deviation from a best fit sphere

Orthogonal Polynomials

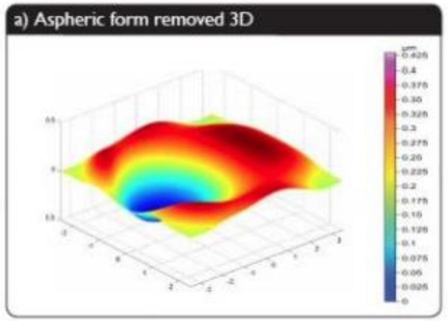
Q^0_n -represents the rotationally symmetric slope-orthogonal Q_{bfs} polynomials

Q^m_n -represents the gradient-orthogonal Q polynomials

קיימים סוגים נוספים של פולינומים...

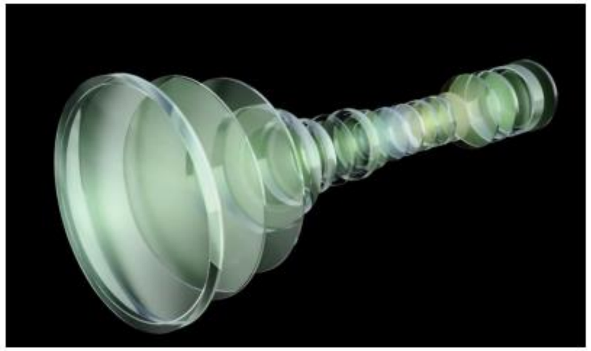
The need for FF

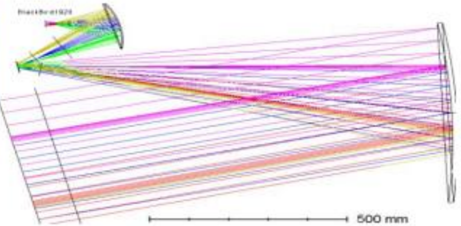
The need for FFO

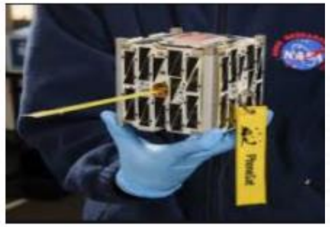


The tradeoff:

High performance = Large & Expensive system



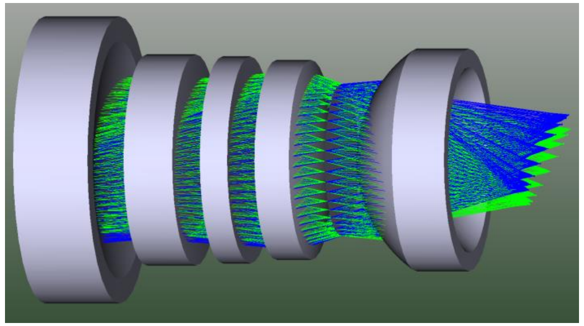


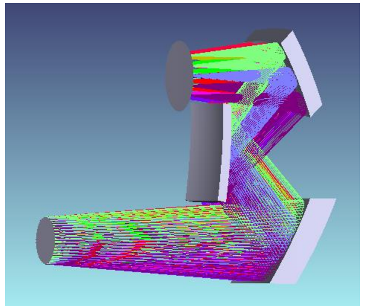


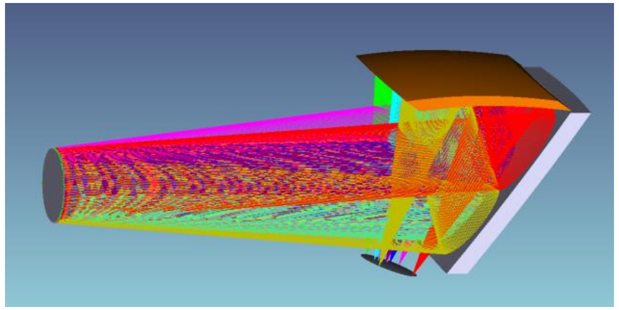
CNC manufacturing of high precision optics enables us to:

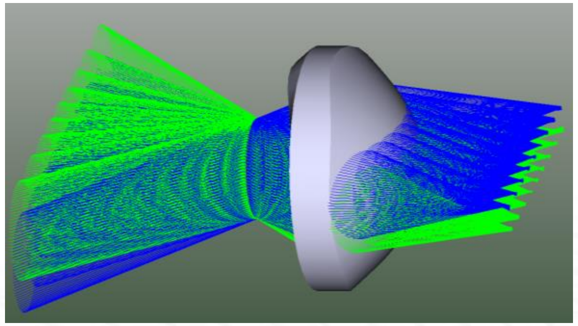
reduce size and cost while optimizing performance

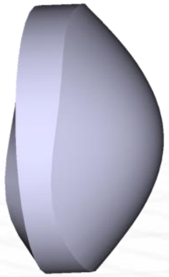
The need for FF

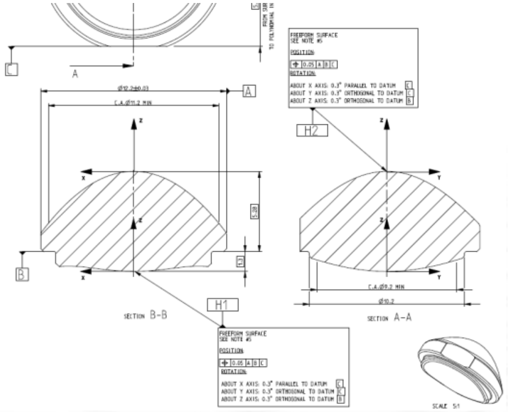






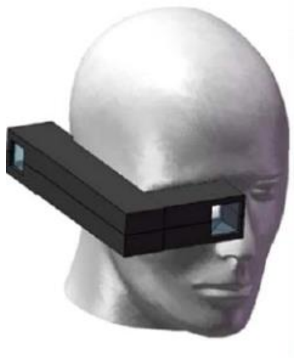




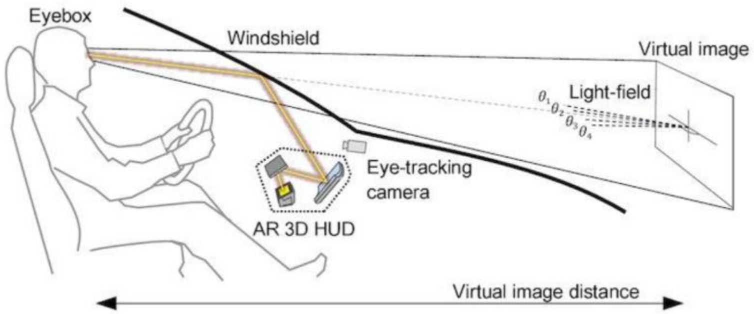


Examples for FF based systems

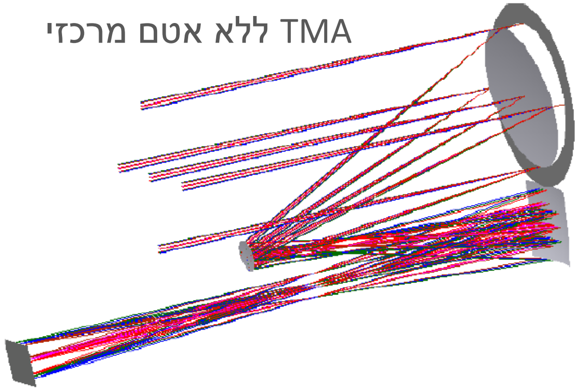
AR/VR



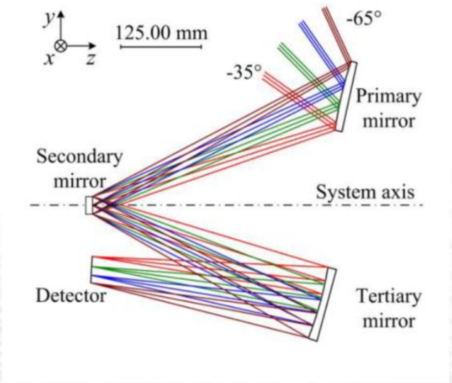
HUD for automotive



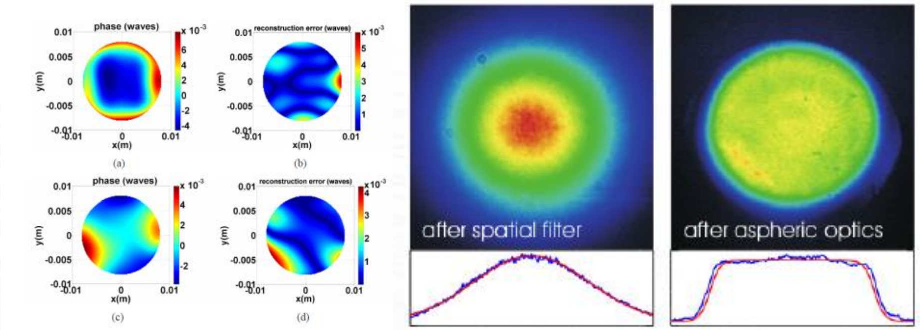
Space telescopes



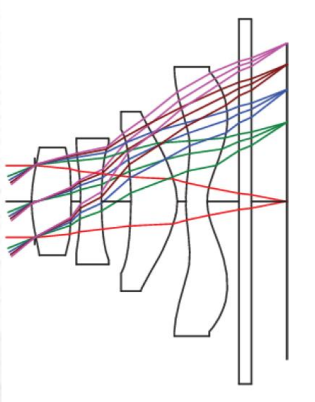
Nonconcentric imaging



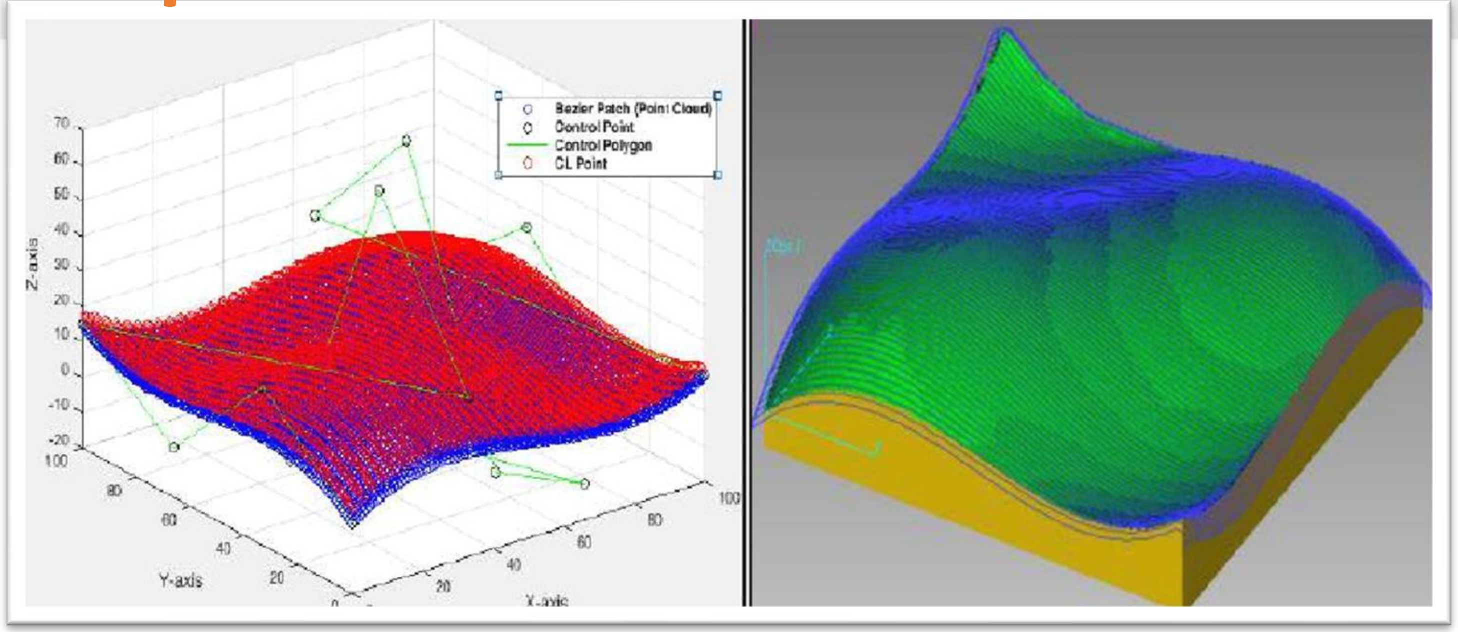
Phase correctors



Optics with severe volume constraints



A-spheric & FF surfaces

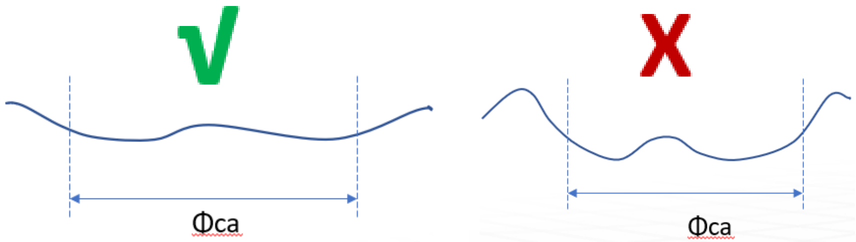


Points cloud

Surface can also be defined in numerical way.

In that case the manufacturer verifies sufficient density for interpolation as well as margins for extrapolation.

Close interaction is needed with the customer.



The choice of the mathematical representation to describe the surface affects the efficiency of the optimization. The geometry of the surface obtained, as a result of the design, determines its manufacturability.

There is no clear method in this matter, and the experience of the optical designer has a lot of weight in the successful choice of the surface representation

Main production technologies

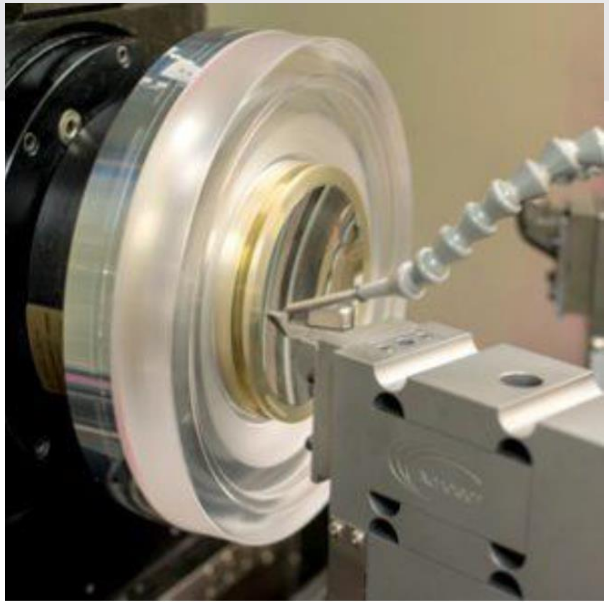
Conventional lapping	Accuracy is guaranteed through a simple and well-defined mechanical mechanism. Suitable for spherical and cylindrical surfaces. High accuracies
SPDT	Enables high precision (principle of operation of a lathe) Limited to producing rotational symmetry(*) and only to "continuous" materials
CNC Grinding & Polishing	Enables the production of all types of surfaces (CNC principle in metal) Two-stage processing (milling + greening) A wide variety of materials It is difficult to achieve high accuracy
Laser grinding & polishing	not yet commercial
MRF- Magneto Rheological Finishing IBF- Ion Beam Finishing	Technologies used for final polishing and minimal Figure-Error
Glass Molding	Economically justified only in large quantities - reduced accuracy

SPO

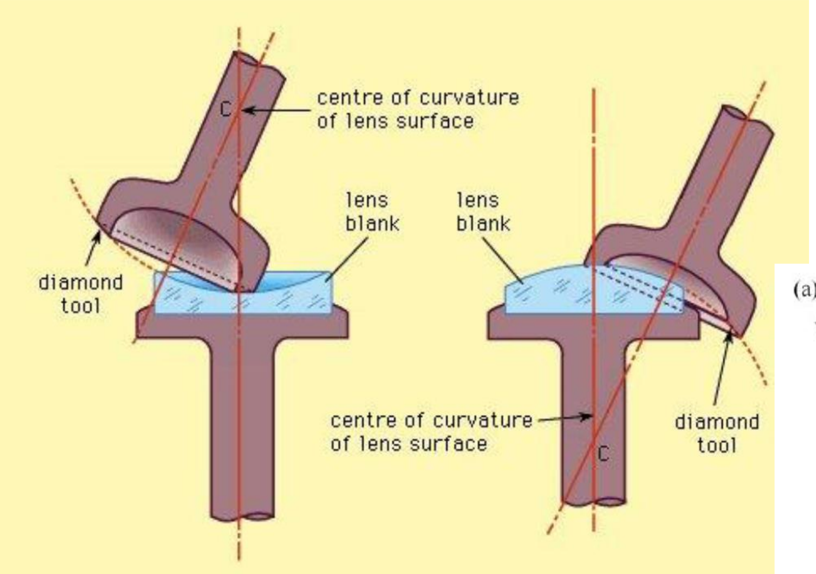
(*) Slow Servo SPDT machines can produce certain types of FFO surfaces

Main production technologies

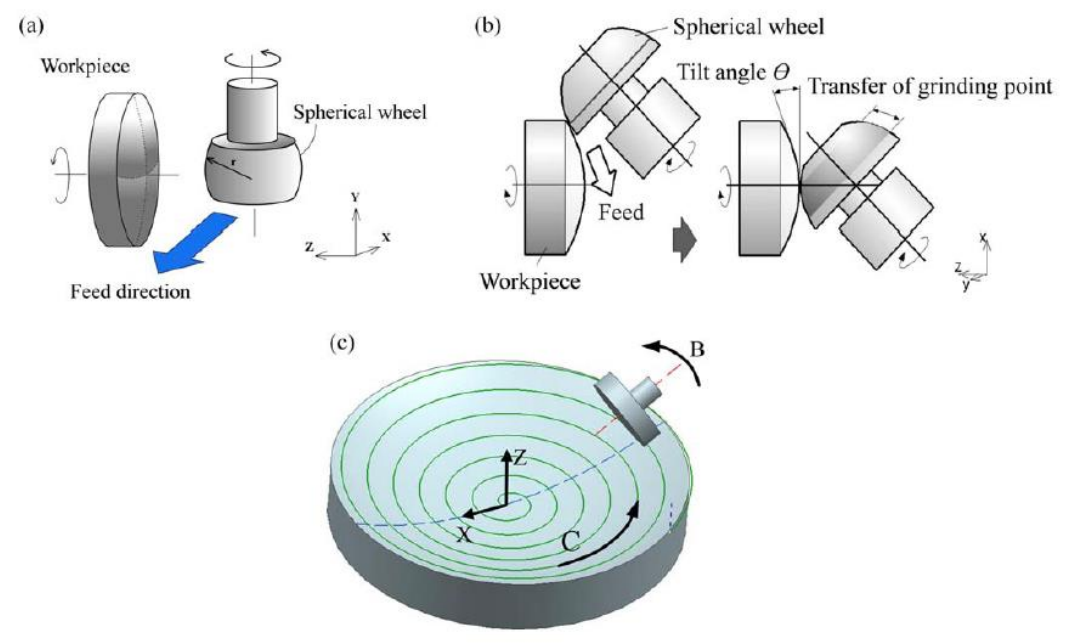
SPDT



Conventional lapping



Grinding & Polishing of Glass



IR Materials

- Germanium
- Zinc Selenide
- Zinc Sulfide
- Chalcogenide Glasses
- Silicon

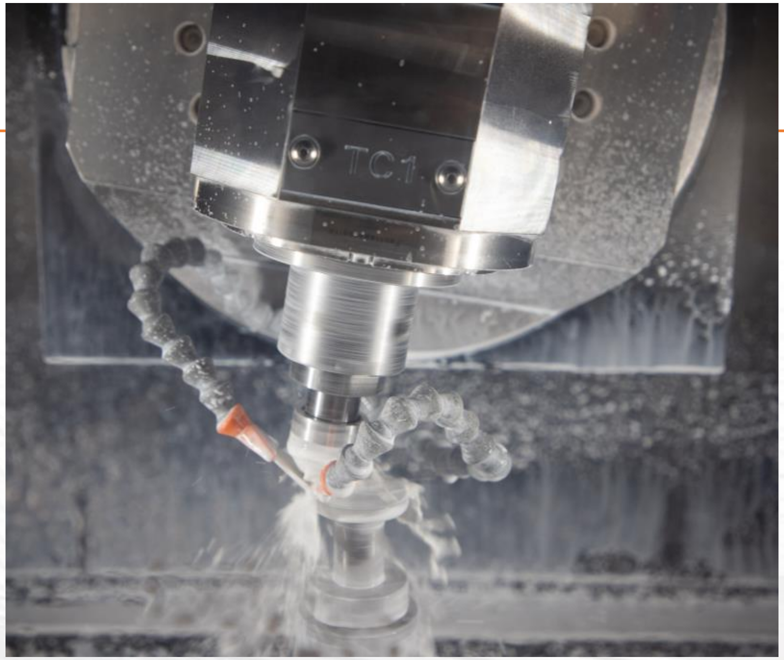
Metal Alloys

Polymers

Multi variable process

$$z(r) = \frac{r^2}{R\left(1+\sqrt{1-(1+\kappa)\frac{r^2}{R^2}}\right)} + \alpha_4 r^4 + \alpha_6 r^6 + \cdots,$$

Many degrees of freedom!



Pressure on surface

Kinematics

Machine errors

Base line errors

Surface measurements

Surface analysis

Correction strategy

Correction errors

Mechanical axis errors

Optic surface definition

Material

Grinding / polishing process of choice

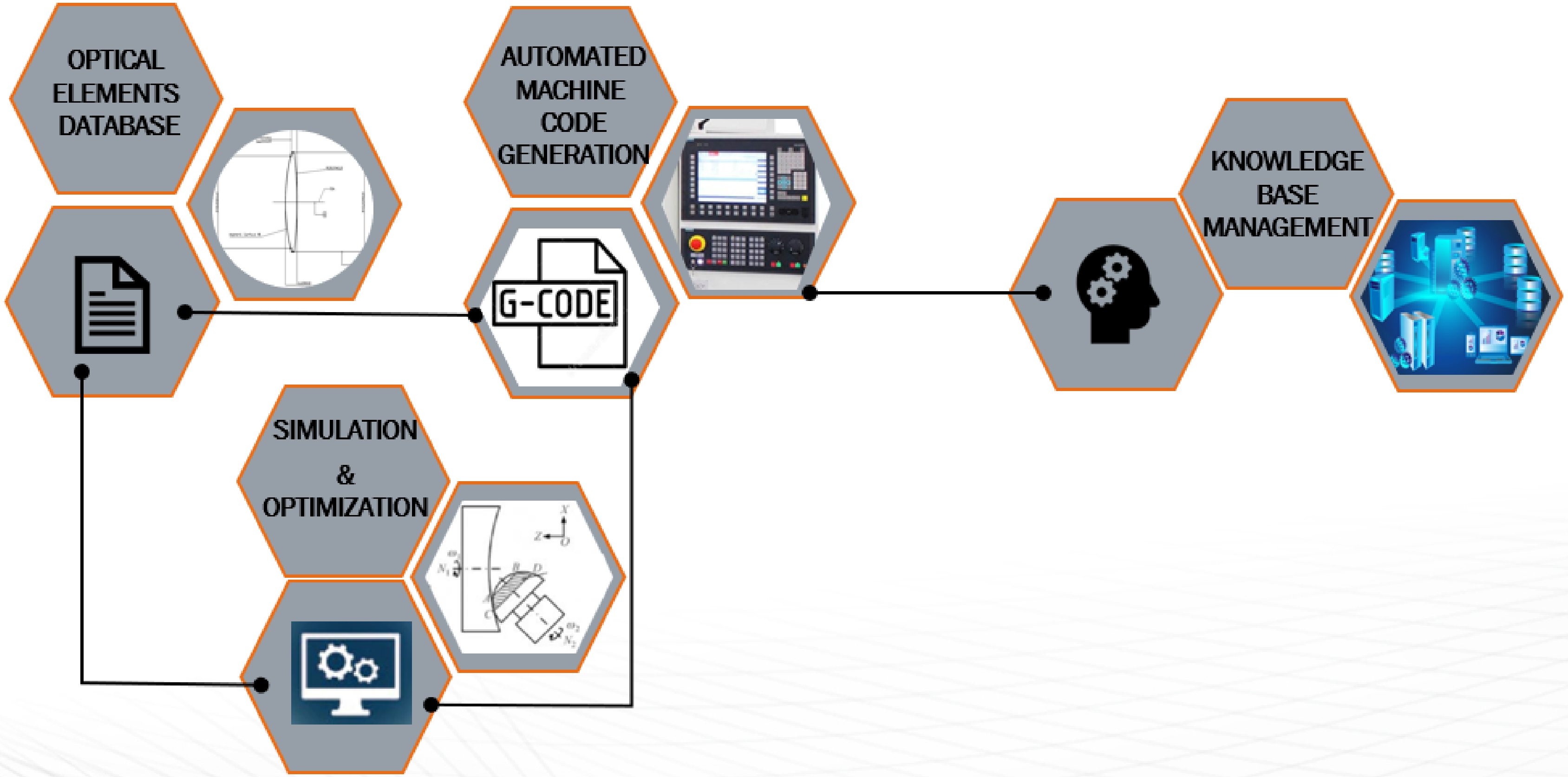
Tool type

Polishing pad type

Polishing slurry

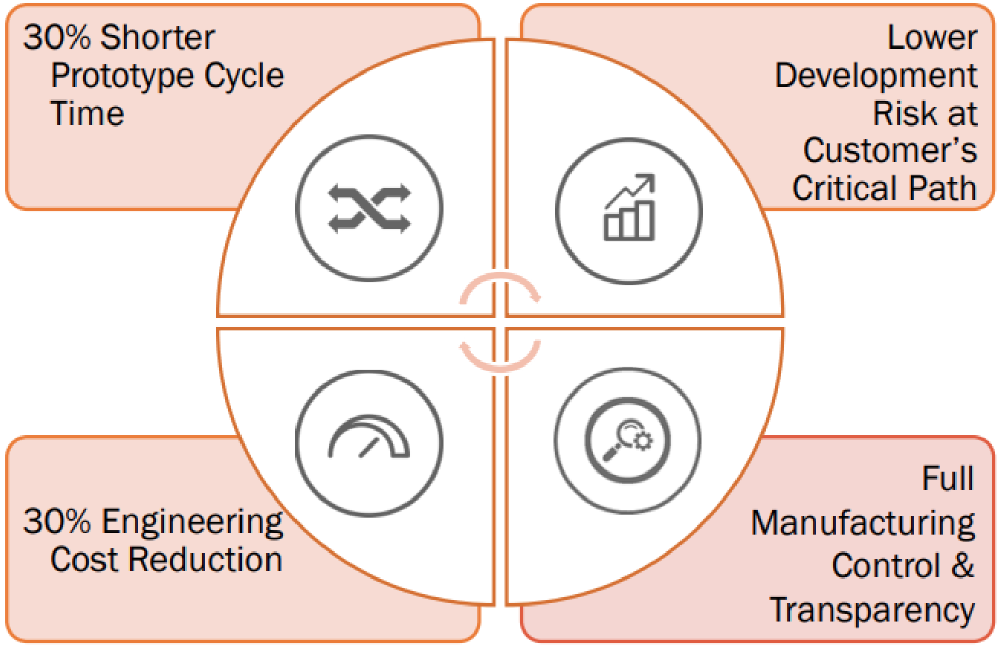
Local material removal rate

Answer – Digital Manufacturing Infrastructure



Digital Manufacturing Infrastructure

DMI: Major benefits for consumers



Thank you