Design principles for an alignment system

and some practical applications using CDS

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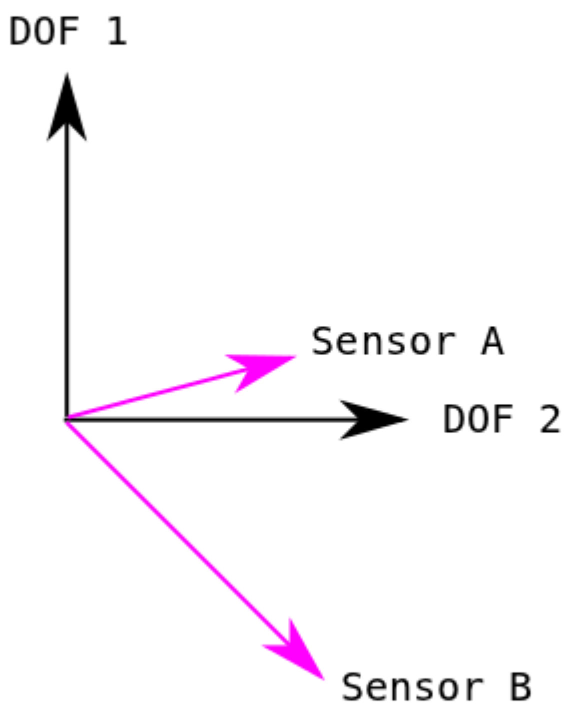
Degrees of freedom

A servo system must be able to sense and control the degrees of freedom of its system.

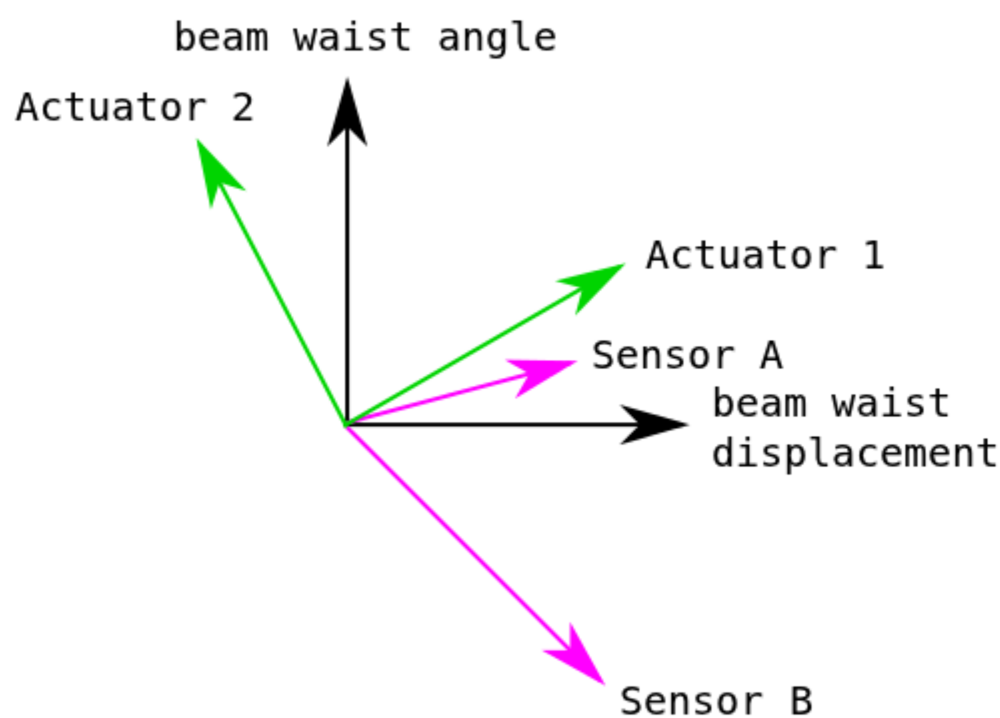


The sensors and the actuators can be represented as vectors in the DOF space.

A good servo has sensors and actuators that sufficiently span the DOF space.

Aligning a laser beam into a cavity

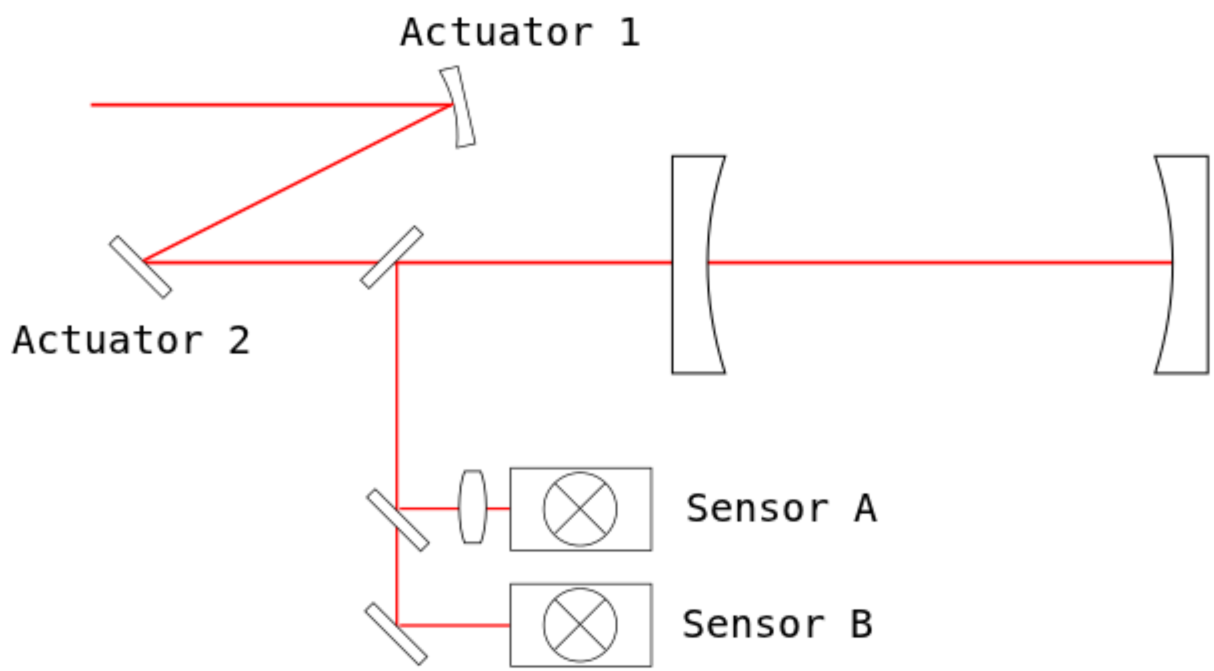
There are 2 DOFs for each of rot and tilt:
- beam waist displacement
- beam waist angle



Aligning a laser beam into a cavity

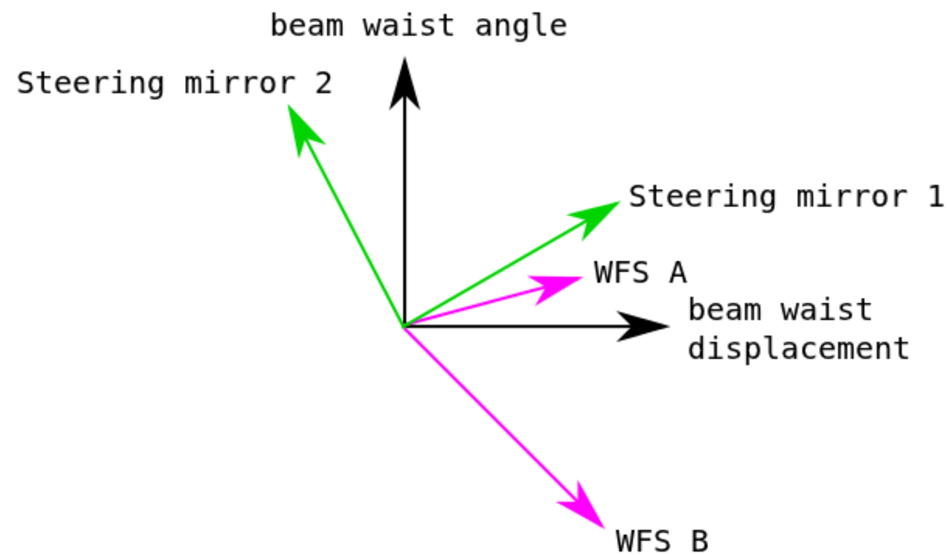
A standard setup uses:

- 2 steering mirrors as actuators
- 2 wavefront sensors (WFS) as sensors
- lenses / curved mirrors

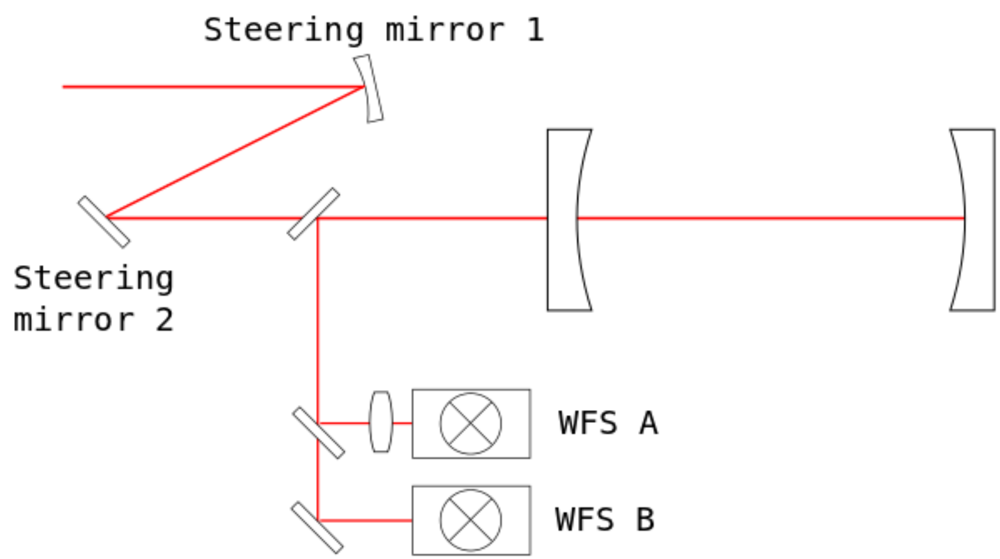


Aligning a laser beam into a cavity

What does it mean to have well-separated sensors or well-separated actuators?



In practice, how do you know the relationship between the sensing and actuation vectors?



The field as a Hermite-Gaussian

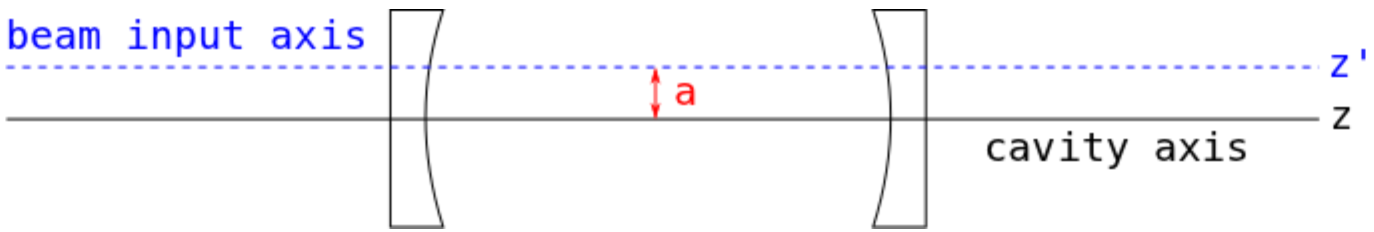
The 2 lowest-order Hermite-Gaussians are:

$$U_0(x) = \left[\frac{2}{\pi x_0^2}\right]^{1/4} e^{-[x/x_0]^2}$$

$$U_1(x) = \frac{2x}{x_0} U_0(x)$$

Representing the field of a misaligned laser beam as a function of HG modes provides insight to what must be sensed/controlled.

Displaced beams

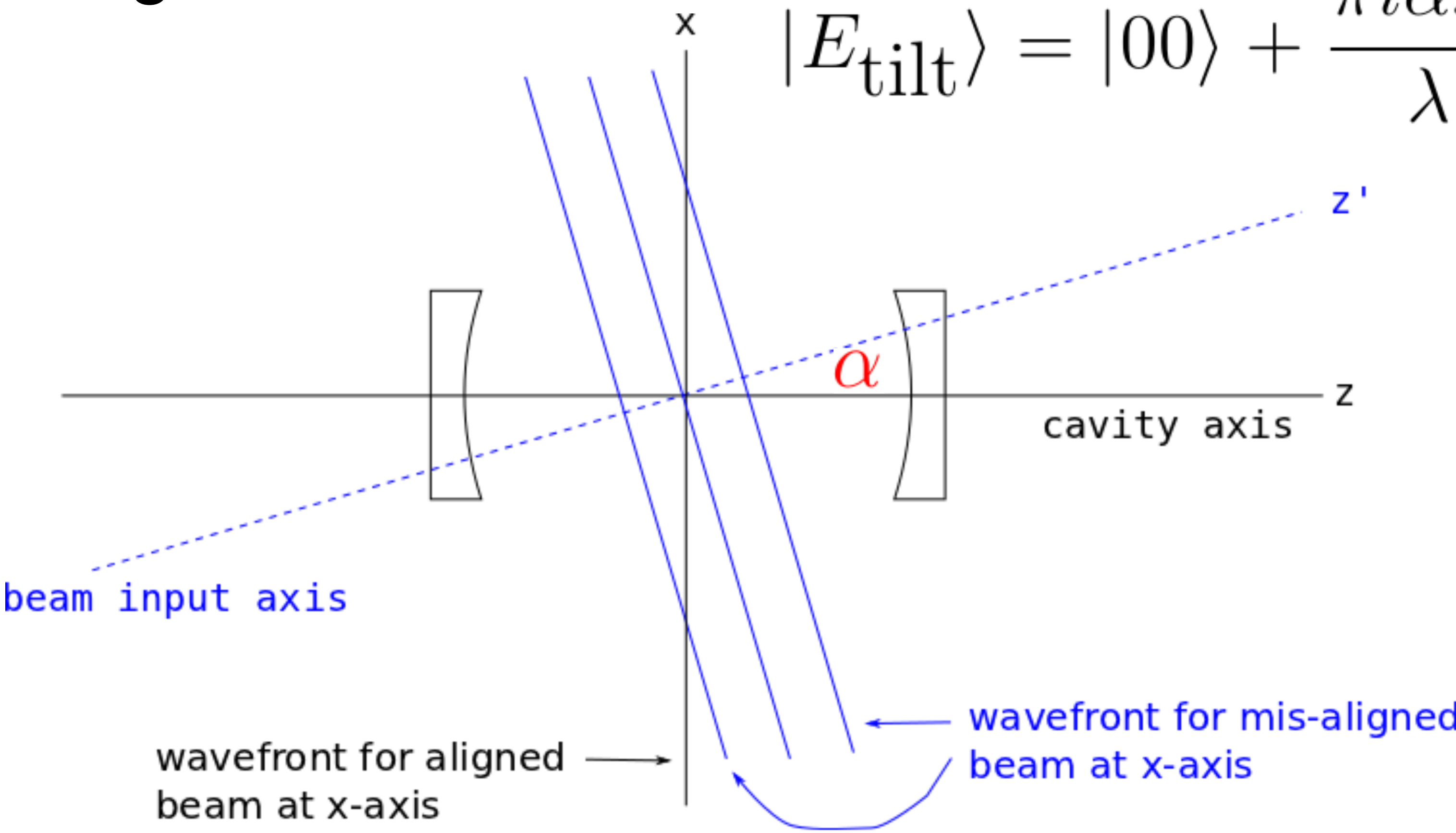


$$|E_{\mathrm{disp}}\rangle = |00\rangle + \frac{a}{x_0}|01\rangle$$

Tilted beam

The tilted beam collects phase for extra path length travelled.

$$|E_{\mathrm{tilt}}\rangle = |00\rangle + \frac{\pi i \alpha x_0}{\lambda}|01\rangle$$



Field of a misaligned beam

A displaced and tilted beam has the following field:

$$|E_{\text{misaligned}}\rangle = |00\rangle + \left[\frac{a}{x_0} + \frac{\pi i \alpha x_0}{\lambda}\right] |01\rangle$$

The alignment system can be thought of as needing to sense and control the real and imaginary parts of the TEM01 field.

Gouy phase separation

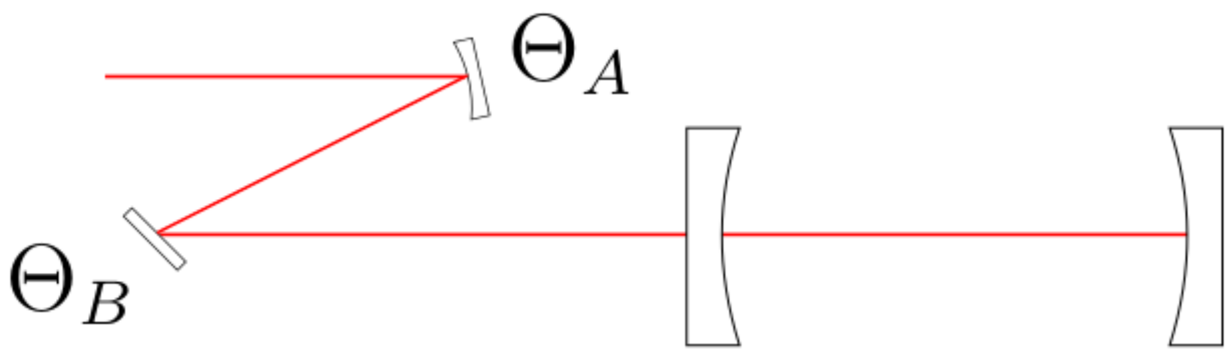
Higher order modes accumulate phase faster than the fundamental mode. This is called the Gouy phase:

$$\eta(z) = -\tan^{-1}\left(\frac{z}{z_R}\right)$$

Gouy phase separation

Upon being actuated on by mirrors A & B which are separated by η :

$$|E\rangle_{\text{out}} = |00\rangle - 2i\left(e^{i\eta}\Theta_{\text{A}} + \Theta_{\text{B}}\right)|01\rangle$$



When η = pi/2, the actuators are 90 deg apart.

Some remarks

- Actuators should be separated by pi/2 radians of Gouy phase
- The same principle holds for sensors; they should be separated by pi/2 radians of Gouy phase
- Designing your Gouy phase telescope while preserving mode-matching can be tricky!
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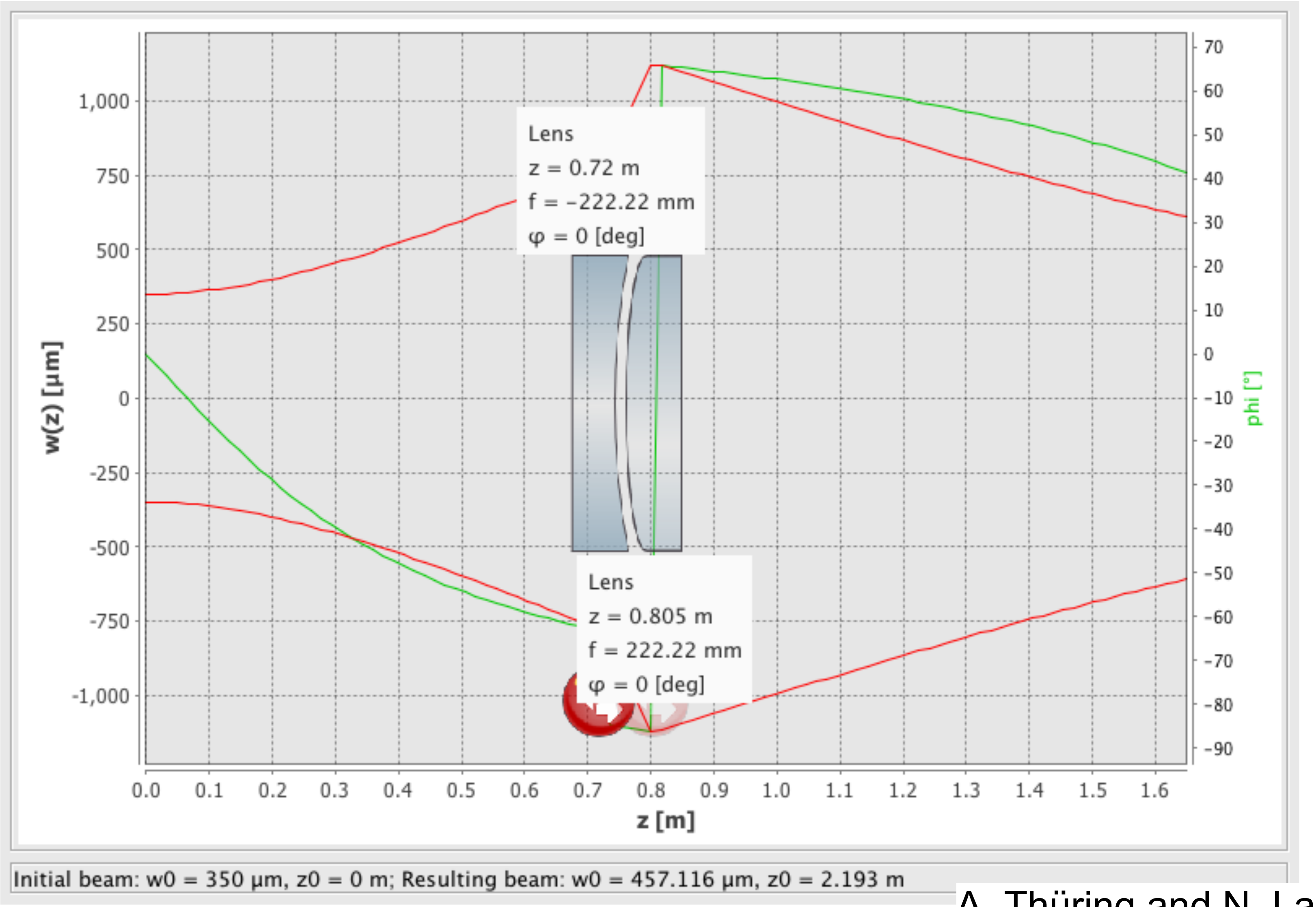
JamMT (Just another mode-matching tool)



A. Thüring and N. Lastzka

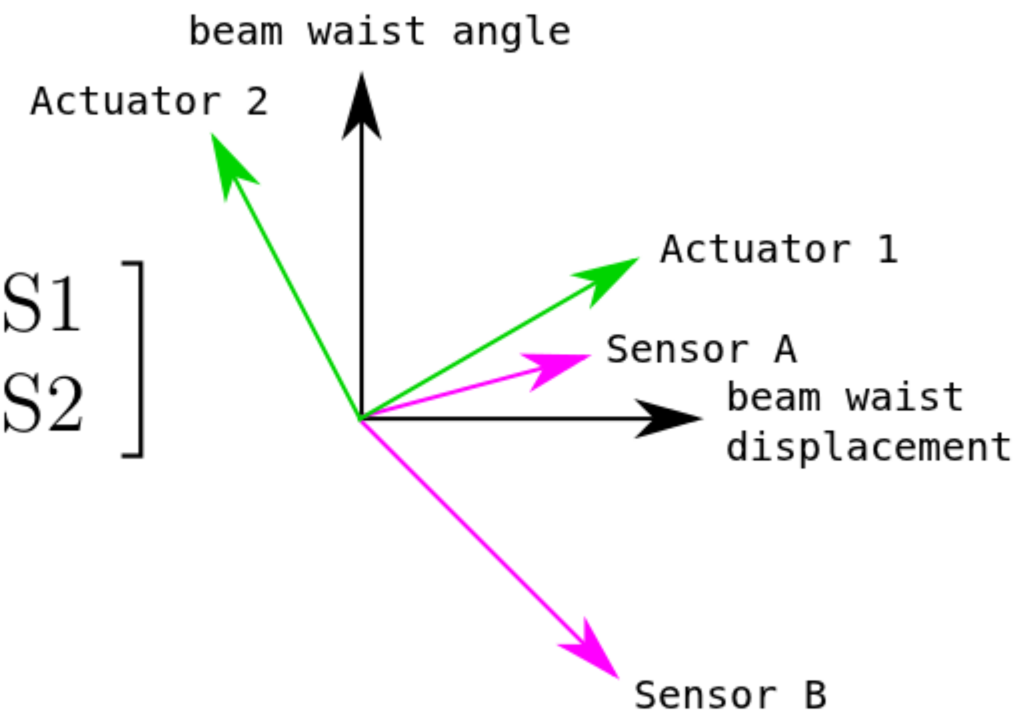
Creating a common basis

Once you've built your system, you need to rotate your signals into the actuator basis.

input matrix

$$\begin{bmatrix} A1 \\ A2 \end{bmatrix} = \begin{bmatrix} ? & ? \\ ? & ? \end{bmatrix} \begin{bmatrix} S1 \\ S2 \end{bmatrix}$$

$$\vec{\mathbf{A}} = \mathbf{M}\vec{\mathbf{S}}$$



Measuring your sensing matrix

In practice, you can measure the inverse of your input matrix, which is also known as the sensing matrix:

$$\vec{\mathbf{S}} = \mathrm{M}^{-1}\vec{\mathbf{A}}$$

Procedure:

1. Excite one of your actuators at frequency f
2. Demodulate your sensor signals at f
3. Repeat for the next mirror

Using CDS to measure your matrix

You can write a shell script that uses command line programs to automate your measurement.

Some "Tools for Detector Scripting" programs:

tdsavg - find the average value of a testpoint over some measurement time

tdssine - inject a sine wave into an excitation point

tdsdmd - demodulate a testpoint at a particular frequency for some number of averages and cycles

tdsresp - combination of tdssine and tdsdmd, to measure transfer matrices at a single frequency

Example TDS usage

pt@pt-ws2 ~ $ tdsavg
USAGE: tdsavg <duration> <chan 0> [<chan 1> ...]

Avgerage channels over some time.
Output is one value per line.

Example usage:
tdsavg 10 H1:LSC-AS1_Q_OUT16 H1:LSC-AS2_Q_OUT16

Pieces of a sensing matrix code

```
#!/bin/csh
set asc = "${ifo}:ASC-"
set sus = "${ifo}:SUS-"

set ctrlDOF = ("DU" "CU" "DS" "CS" "RM")

set A_DRIVE = "300"
set F_DRIVE = "9.7"
set N_AVE = "10"
set N_CYCLE = "30"
set TDS_ARGS = "$F_DRIVE $A_DRIVE $N_CYCLE $N_AVE"

foreach i (1 2 3 4 5)
   set dof  = $ctrlDOF[$i]
   echo Excitation on  $dof PIT
   $tdsresp $TDS_ARGS  ${ifo}:ASC-WFS5${STIM_PIT}  $PIT_CHANS >> $PIT_FILE
   echo Excitation  on  $dof YAW
   $tdsresp $TDS_ARGS  ${ifo}:ASC-WFS5${STIM_YAW}  $YAW_CHANS >> $YAW_FILE
end
```

Sensing matrix output

You get a text file that looks like this:

coh, mag, phi, re, im, err_re err_im

```
1 150.68 -1.21593 52.3555 -141.292 0.334324 0.901891
0.993772 1.93556e-05 -0.559652 1.64027e-05 -1.02757e-05 4.06544e-07 7.65756e-07
0.998928 2.03558e-05 -0.58934 1.6922e-05 -1.1314e-05 3.53317e-07 3.15715e-07
0.997486 3.84008e-05 -0.54548 3.2828e-05 -1.99235e-05 7.24852e-07 1.12998e-06
0.993365 3.83202e-05 -0.668876 3.00629e-05 -2.37625e-05 1.36009e-06 1.27578e-06
0.0566898 1.33427e-06 1.36794 2.68818e-07 1.30691e-06 4.17021e-06 9.10711e-06
```

You need to then write a script (ie. in Matlab) to extract your transfer coefficients from this data and take the inverse of your sensing matrix.

final thoughts

- want to match cavity and input laser to one another --> you can change either one of them

- use JamMT (or your own code!) to design your 90 Gouy phase separation between sensors and actuators

- make use of CDS's tools to measure your sensing matrix

References

- "Lasers" by Siegman
- Alignment of Resonant Optical Cavities. Dana Anderson, Applied Optics Vol. 23, Issue 7, 1984
- Nicolas Smith thesis
- Kate Dooley thesis
- JamMT http://www.sr.bham.ac.uk/dokuwiki/doku.php?id=geosim:jammt
- A la Mode http://web.mit.edu/nicolas/www/alm/alm.html