Kinematics for high stability mirror systems

Combined motion control for a 5 axis mirror system by

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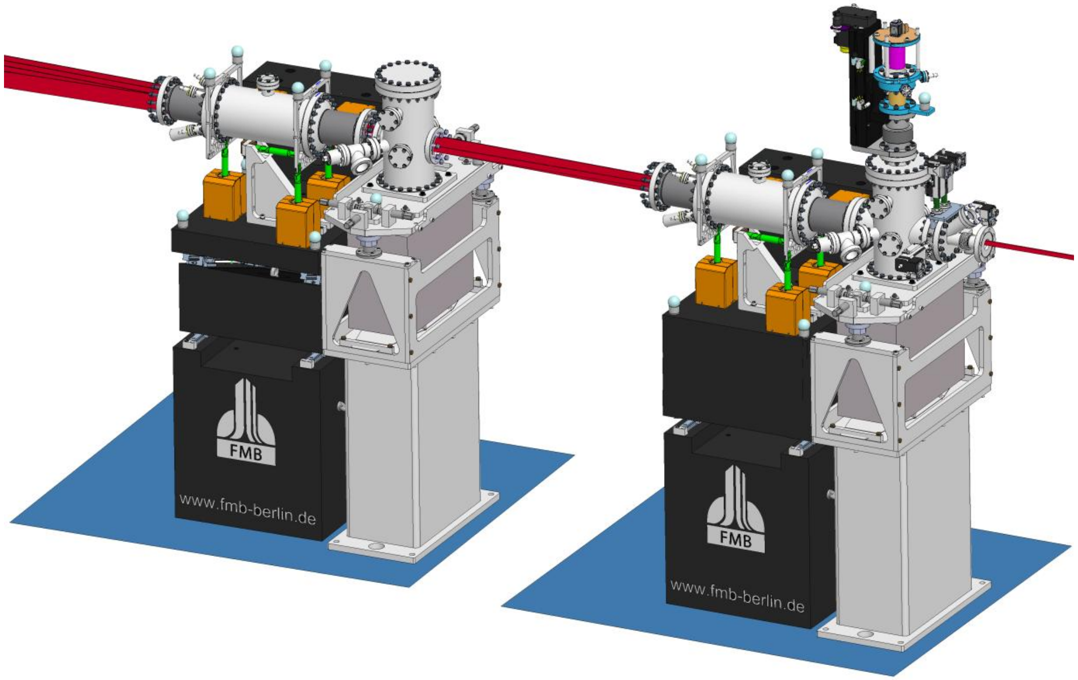
Combined multi axis motion control with GeoBrick /PMAC

Mirrors in synchrotron beamlines



Task: guiding synchrotron radiation to
experiments or switching between different targets
Difficulties: Very tiny angles and low vibration requirements

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Mirror Chamber

- 5 moveable leg-drives
- 1 fixed leg
- granite foundation
- Flexure joints for all necessary movements
- +/- 5mm distance range of each legdrive
- +/- 10 mrad tilting angle limited by vacuum bellows

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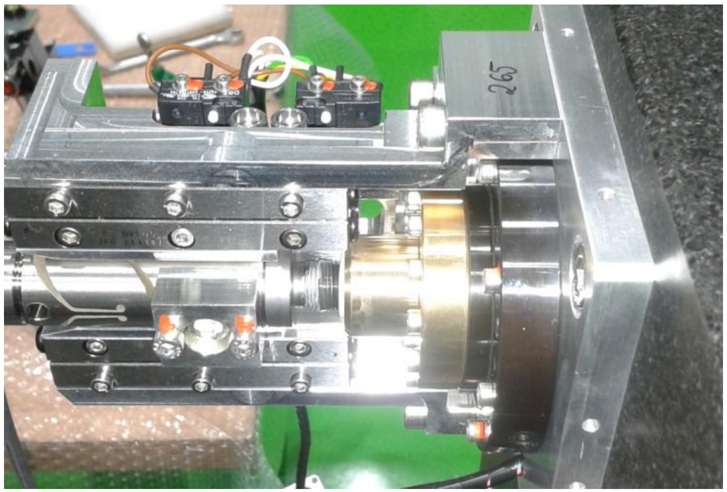
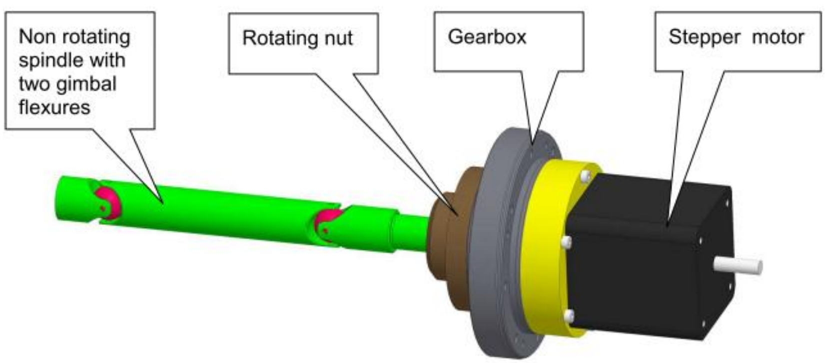
Leg drive





- High precision linear ball bearing slide
- Limit and overtravel switches
- 1nm resolution linear absolute optic encoder
- 1/100 harmonic drive gear
- 400/turn stepper motor

Motion controller HPMC-8

- 8 motor amplifier outputs
- 8 absolute or incremental encoder inputs
- Additional digital and analogue in/outputs
- Based on DELTA TAU GeoBrickLV motion ctrl.
- Internal Power Supply
- Embedded Computer

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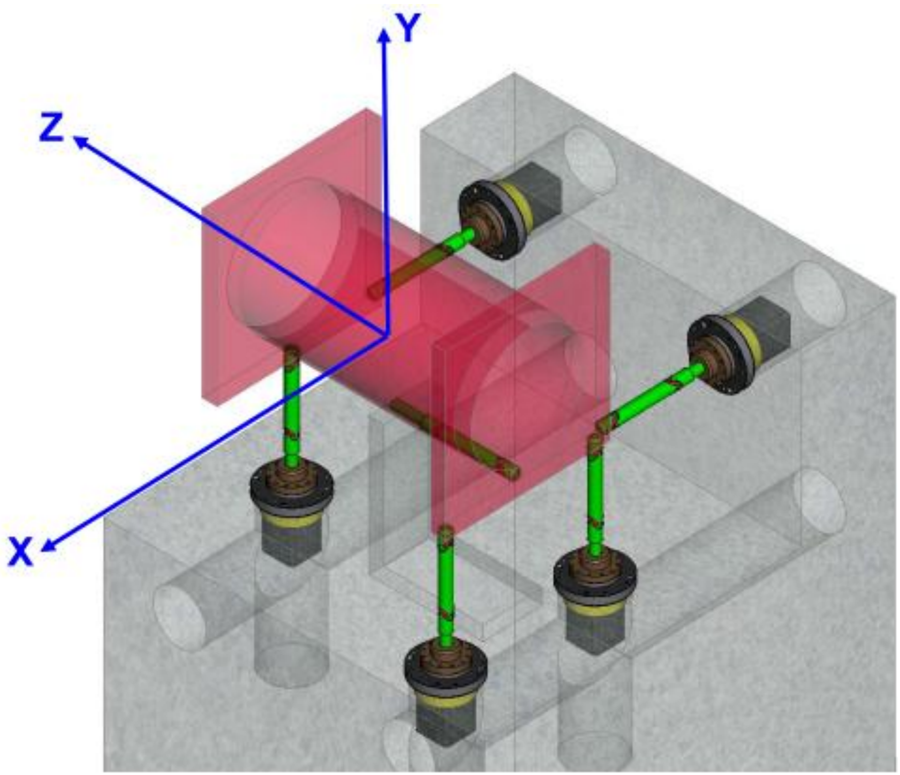
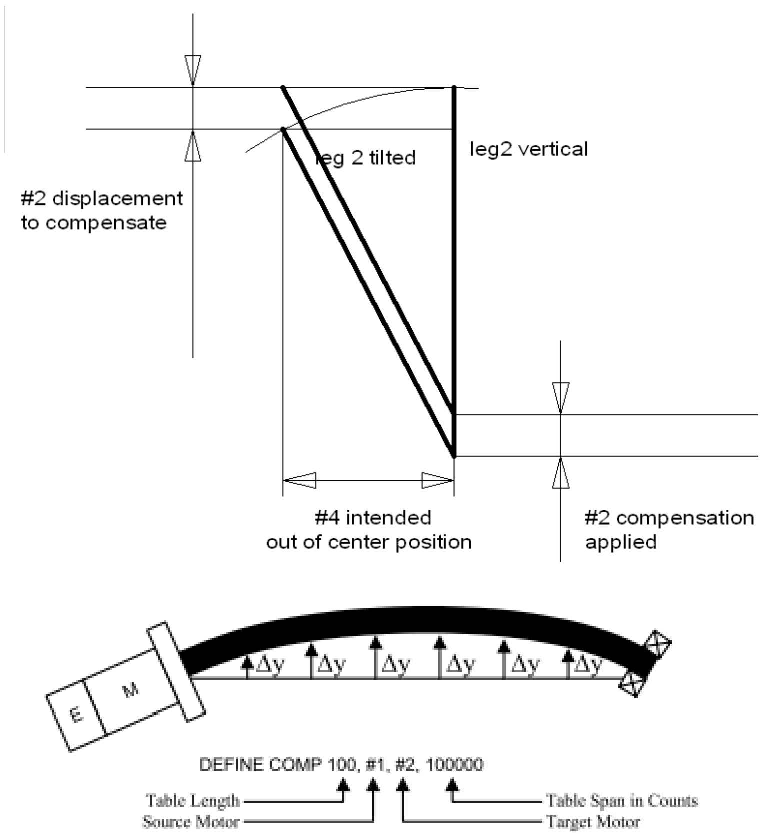
3-dimensional degrees of freedom



- Translation in X and Y direction
- Rotation around X axis (Yaw*)
- Rotation around Y axis (Pitch*)
- Rotation around Z axis (Roll*)

* for a side bounce mirror

Cross axis compensation movement



Source: PMAC User Manual

- Δy=f(x;D_gimbal)
- Calculated compensation values in Excel-spreadsheat for PMAC compensation tables
- Y1 and Y2 comp. X4
- Y3 compensates X5
- X4 compensates Y2
- X5 compensates Y3

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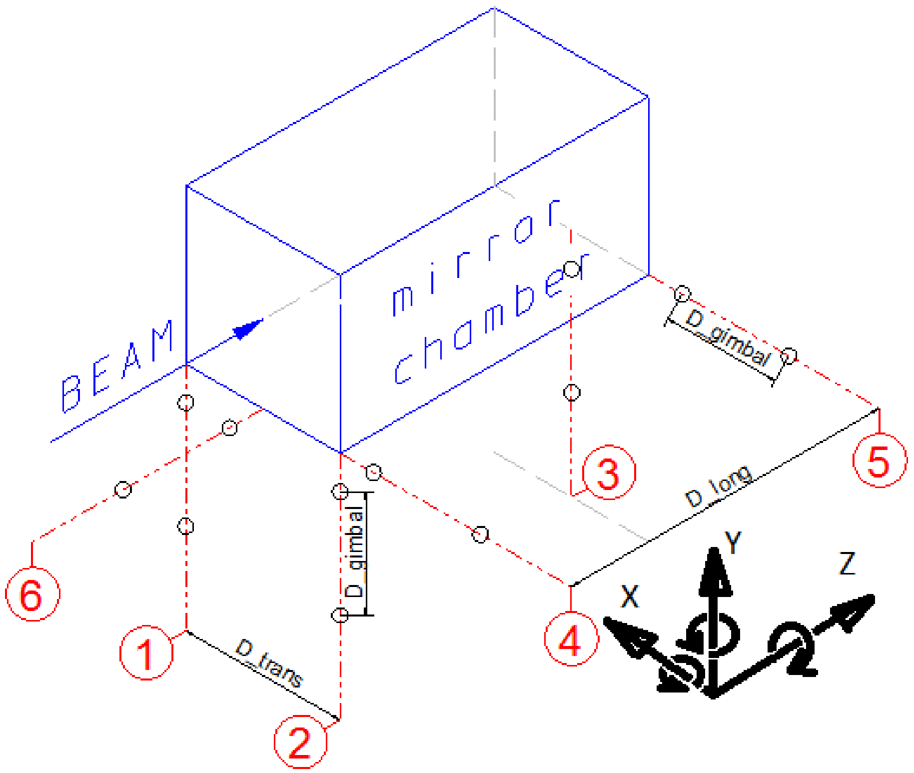
Kinematic calculations



- Development of kinematic calculations in another Excel sheet
- Forward kinematic: coordinate system to single drive position
- Inverse kinematic: Encoder position to coordinate positions

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	A	B	C	D	E	F	G	H	I	J	K
1	**Kinematic Calculations for 5-Leg Mirror System**										
2	including compensation for lateral displacement while RotZ motion										
3	without lever compensation which is done with compensation tables on the motion controller										
4											
5	Explanations:		User Input			Calculated Results					
6											
7			Parameter Input								
8	D (longitudinal)		300	mm							
9	D (transversal)		220	mm							
10	D (gimbal)		100	mm	noch nicht implementiert						
11	RZ max	±	10	mrad	noch nicht implementiert						
12											
13	**Motor (Leg)**		**Input**		**Intermediate Results**					**Calculated Positions**	
14			**Forward Kinematic**		calc. RotY	calc. RotZ	calc. RotX	calc. Vertical	calc. Lateral	**Forward Kinematic**	
15	Y1	#1	2,943	**mm**		2,94296027	0	0		**2,943**	**mm**
16	Y2	#2	0,963	**mm**		0,962987	0	0		**0,963**	**mm**
17	Y3	#3	1,953	**mm**		1,952973635	0	0		**1,953**	**mm**
18	X1	#4	1,449	**mm**	0	1,448980439			0	**1,449**	**mm**
19	X2	#5	1,449	**mm**	0	1,448980439			0	**1,449**	**mm**
20	Z1	#6	0,000	mm	0		0		0	**0,000**	**mm**
21	**Compound Movement for a side bounce Mirror**									**Inverse Kinematic**	
22	RotZ	RZ	9,000	**mrad**		9				**9,000**	**mrad**
23	RotX	RX	0,000	**mrad**			0			**0,000**	**mrad**
24	RotY	RY	0,000	**mrad**	0					**0,000**	**mrad**
25	Vertical	TY	0,000	**mm**		1,952973635	0	1,952973635		**0,000**	**mm**
26	Lateral	TX	0,000	**mm**	0	1,448980439			1,44898044	**0,000**	**mm**
27	Axial	TZ	0,000	mm	0		0		0	**0,000**	**mm**
28	**shift rotation axis in both perpendicular directions**									**Angular Limit**	
29	RotZshiftY	RZSY	51,000	**mm**					absRXZ	9	**mrad**
30	RotZshiftX	RZSX	-217,000	**mm**					absRXY	0	**mrad**
31	RotXshiftY	RXSY	0,000	mm					absRYZ	9	**mrad**
32	RotXshiftZ	RXSZ	150,000	**mm**					absRXYZ	9	**mrad**
33	RotYshiftX	RYSX	0,000	mm							
34	RotYshiftZ	RYSZ	150,000	**mm**				only with Z-Axis (Z1 #6) drive possible			

Implementation in Delta Tau PMAC

- PMAC code derived from Excel formulae
- First programmed PLC to calculate angles and positions from Motor positions (Inv. Kinematic)
- Implemented forward and inverse kinematic in PMAC code
- Tested with simulated drives on PMAC hardware
- Then using real Mirror chambers
- Verification with Interferrometer and Autocollimator Measurements using FMB´s DriveAnalyzer software

Substitution File

```
#define Rot_Z      Q1        ; Roll angle of Mirror axis letter A M5141
#define Rot_X      Q2        ; Yaw angle of Mirror axis letter B M5142
#define Rot_Y      Q3        ; Pitch angle of Mirror axis letter C M5143
#define Vertical   Q4        ; vertical displacement of Mirror axis letter U M5144
#define Lateral    Q5        ; lateral displacement of Mirror axis letter V M5145
#define Axial      Q6        ; Axial displacement of Mirror axis letter W M5146

#define Y1Pos      P1        ; leg Y1 position in Counts
#define Y2Pos      P2        ; leg Y2 position in Counts
#define Y3Pos      P3        ; leg Y3 position in Counts
#define X1Pos      P4        ; leg X1 position in Counts
#define X2Pos      P5        ; leg X2 position in Counts
#define ZPos       P6        ; leg Z position in Counts for now immobile

#define L_LONG   P1001       ;longitudal lever lenght
#define L_LAT    P1002       ;lateral lever lenght
#define ComRot_Z P1003       ; Commanded Roll angle[°] in motion program
#define ComRot_X P1004       ; Commanded Yaw angle[°] in motion program
#define ComRot_Y P1005       ; Commanded Pitch angle[°] in motion program
#define ComVertical P1006    ; Commanded Vertical displacement[mm] in motion
        program
#define ComLateral P1007     ; Commanded Lateral displacement[mm] in motion
        program
#define ComAxial P1008       ; Commanded Axial displacement[mm] in motion
        program is allways zero without Z-Motor
…
```

- Defining substitute names for all Variables used in PLC and Kinematic calculations
- Using the same names in Excel makes copying source code easy

PLC and fwd/inv. kinematics File

```
;The following are PLC programs..........................................
;
;initial values #include
        "N:\software\pmac\5+1LegMirror\axisshift\5plus1LegMir_macro_substitutions_Axishift.p
        mc"

; Forward Kinematic PLC Programm Buffer for mirror position from Axis position reporting
OPEN PLC 10 CLEAR

IF (Mot1HomCmplt=1 AND Mot2HomCmplt=1 AND Mot3HomCmplt=1 AND Mot4HomCmplt=1
        AND Mot5HomCmplt=1 )       ; Properly position referenced ?
        PLCY1Pos=(M1ActPosCts+M1PosOffSet+M1PosComp)/(i108*32*Cts2mm)
                    ;axis position in mm
        PLCY2Pos=(M2ActPosCts+M2PosOffSet+M2PosComp)/(i208*32*Cts2mm)
                    ;axis position in mm
        ...
        PLCZPos=(M6ActPosCts+M6PosOffSet+M6PosComp)/(i608*32*Cts2mm)
                    ;axis position in mm

        CalcRot_Z=ASIN((PLCY1Pos-PLCY2Pos)/L_LAT)/Milli ;Roll Position in mrad
        CalcRot_X=ASIN((((PLCY1Pos+PLCY2Pos)/2)-PLCY3Pos)/L_LONG)/Milli    ;Yaw Position in
        mrad
        CalcRot_Y=ASIN((PLCX1Pos-PLCX2Pos)/L_LONG)/Milli                   ; Pitch position in
        mrad
        CalcVertical=(((PLCY1Pos+PLCY2Pos)/2)+PLCY3Pos)/2-
        (SIN(1000*(ASIN((((PLCY1Pos+PLCY2Pos)/2)-PLCY3Pos)/L_LONG)/1000))*RotXshiftZ)-
        (SIN((1000*(ASIN((PLCY1Pos-PLCY2Pos)/L_LAT))/1000))*(-RotZshiftX))   ;vertical position
        in mm

        CalcLateral=((PLCX1Pos+PLCX2Pos)/2)-(SIN(1000*(ASIN((PLCY1Pos-
        PLCY2Pos)/L_LAT))/1000)*(L_LAT/2+RotZshiftY))-SIN(ASIN((PLCX1Pos-
        PLCX2Pos)/L_LONG))*(RotYshiftZ)                    ; lateral position in mm
        CalcAxial=PLCZPos-(SIN(ASIN(((PLCY1Pos+PLCY2Pos)/2-PLCY3Pos)/L_LONG))*(L_LAT/-2-
        RotXshiftY))-SIN((ASIN((PLCX1Pos-PLCX2Pos)/L_LONG)))*(RotYshiftX) ...
```

- PLC converts motor position counts to engineering values and calculates Angles and positions
- also guards geometrically added angle values for exceeding boundaries and stopping coordinate system movement if necessary
- Simple motion program

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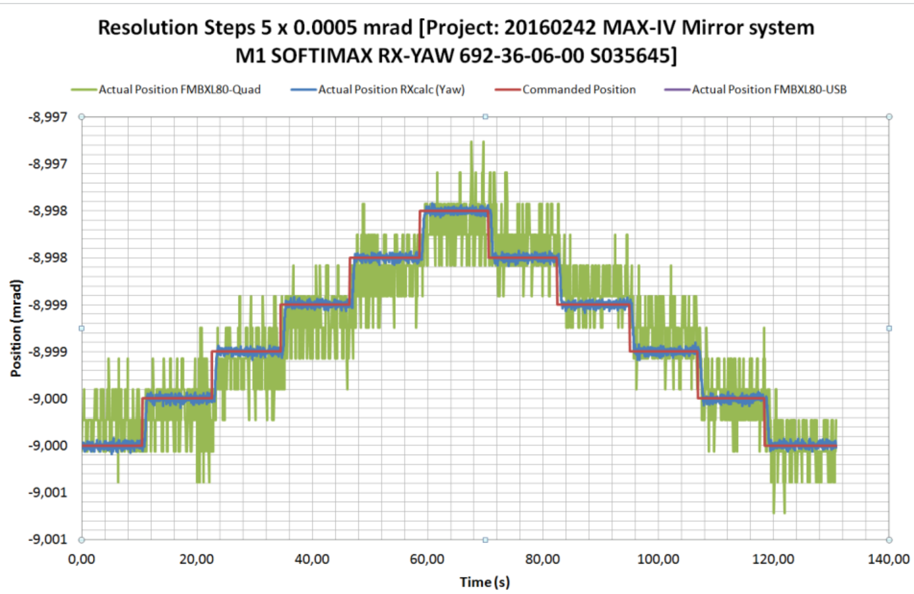
Drive Analyzer Tests



- DA is an automated test procedure for all kinds of motorized drives
- It comunicates with PMAC motion controllers to command movement and log encoder values or other measurement devices as well as status variables

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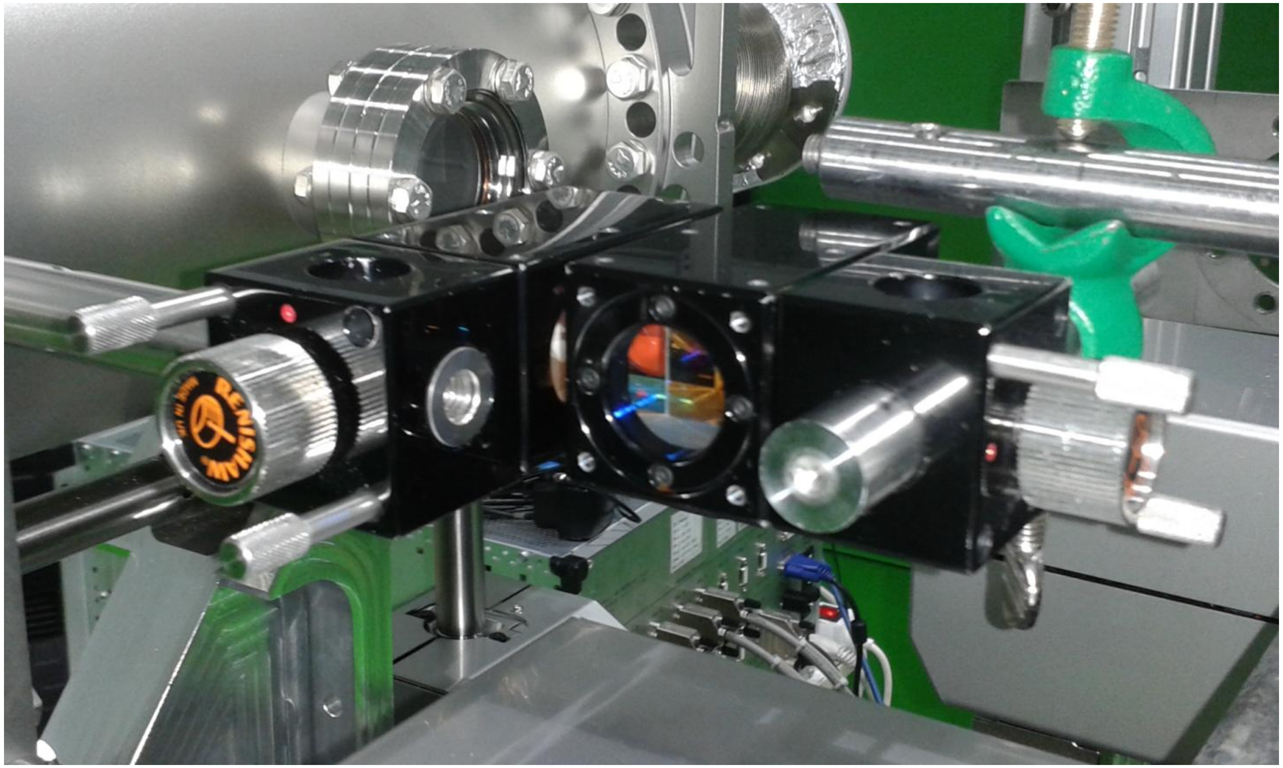

Interferrometer optics mounted on mirror chamber for pitch angle movement measurement

With a renishaw XL80 Laser interferrometer we checked if the calculated angles and distances match with real world measured values

Such tiny differences are difficult to measure close to the resolution limit of the XL80

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Software Improvements

- In software protection against vacuum bellow damage through excessive bending
- Implementation of the ability to shift rotation axes
- This also improved the range of interferrometer measurements by moving the rotation axes into the interferometer optics

To-Do-List

- Improved angle limit behaviour, maybe by using the motor software limits
- Adding the 6th motorized axis for full compensation and axis shifting capabilities
- User interface in EPICS / TANGO or other GUI
- Writing motion programs for scanning and angle sweeps

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Any Questions?

- Has someone experience in programming kinematics on an IcePAP controller?
- Has anyone some experience with negative backlash in linear guide drives with closed loop feedback?

Thank you!