Dealing with friction in a reusable 6 degrees of freedom adjustment mechanism with sliding contacts

Friso Klinkhamer*, TNO TPD, Delft, the Netherlands

ABSTRACT

Although the possibility of a 6 degrees of freedom adjustment based on a single body pulled onto on six adjustable supports follows directly from the kinematic theory, such mechanisms are seldom used in actual products. Two major drawbacks for the use of this solution are:

- Due to the sliding contact between the body and the supports, friction will occur and may inhibit movement.
- Coupling between the adjusted axes cannot be avoided, this may interfere with the necessity of an adjustment procedure with a limited number of iterations

This paper presents a matrix calculation method that offers a prediction whether the body will move as required, depending on the position of the supports and on the magnitude of the friction. This method enables to check the functionality of a design. This method has been used in the design of several adjustment mechanisms consisting of a body pulled onto six supports.

The matrix calculation method also allows predicting the movement of the adjusted body due to adjustment of the separate supports. Using this it is relatively simple to simulate the movements that an operator will observe, and in this way check whether an operator is capable to handle the couplings present in the adjustment. Using the simulation the adjustment procedure can be optimized.

Keywords: Opto-mechanics, adjustment, adjustment procedure, degrees of freedom

1. INTRODUCTION

The need for a 6 Degrees of freedom adjustment was identified in the development of a calibration sensor in the twin stage wafer-scanners of ASML [1]. This calibration sensor has to measure the wafer height with an accuracy of better than ± 5 nm.

The sensor is based on the triangulation principle: a light spot is projected on the wafer; the position of the reflected spot is determined, see Figure 1. The light spot is created in the 'illumination optics' and projected on the wafer by a telecentric lens. The position of the light spot on the wafer has to be accurate within 3 um (most critical direction). This tolerance in the position of the image of the light spot is influenced by the tolerance in the position of the light spot in front of the optics (the object), but more important by imperfections of the optics.

In the concept phase it was decided that:

- optics with relatively large variation in focus distance and ‘bore-sight error’ would be used
- this optics would be mounted in a fixed position
- the light spot (the object) would be mounted in a body that could be adjusted in all relevant degrees of freedom to compensate for the errors in optics and the mounting

This approach meant that the adjustment mechanism had the following (generalized) requirements:

- adjustable in 6 degrees of freedom
- range: ± 1 mm (translational), ± 20 mrad (rotational)
- accuracy: ± 3 um (translational), ± 100 urad (rotational) (this included the accuracy of the measurement tool)
- short term stability (5 minutes): ± 1 nm (translational), ± 20 nrad (rotational)
- small volume

* klinkhamer@tpd.tno.nl, POB 155, 2600 AD, Delft, the Netherlands

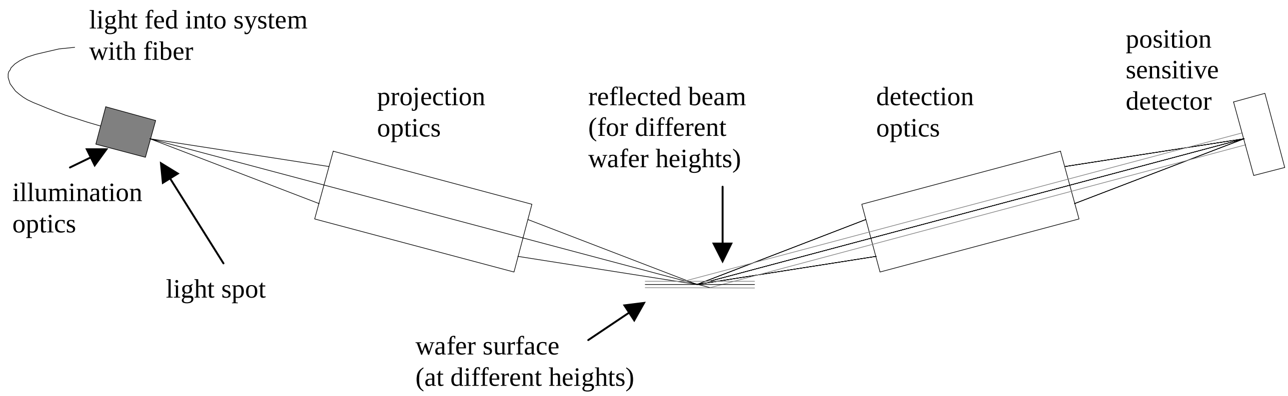

Figure 1: Schematic view of the calibration sensor. The illumination optics has to be adjusted in the 6 degrees of freedom.

2. THE MECHANICAL CONCEPT

In the choice of the concept the following consideration turned out to be the most important:

- In order to meet the severe stability requirement, the number of mechanical interfaces between the frame and the adjusted body shall be minimized. The rule is based on the following empirical observation: each interface between the ground and the final adjusted body endangers the stability of the adjusted body. This empirical observation is tentatively explained by the presence of stress concentrations and possibilities of micro-creep in the interfaces.

Based on this consideration a concept where the adjustable body was pulled on six separately adjustable supports was chosen. This concept uses the familiar result of kinematic design: the position of a body can be fully determined by six point supports. A single force can serve to guarantee contact between the body and all six supports [2, 3, 4]. If one support is retracted, the body will have to move in order to maintain contact with all six supports, see Figure 2. It was envisioned that an adjustment mechanism based on this concept would combine low complexity with low volume and high stability (low number of mechanical interfaces between frame and adjusted body, stiff contact points), while complying with the requirements on range and accuracy.

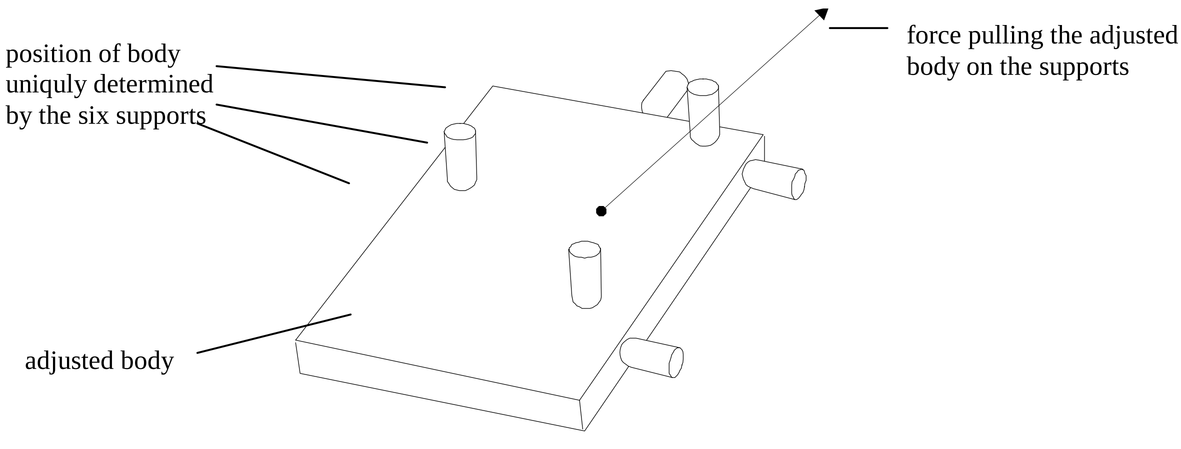

Figure 2: Selected mechanical concept for the 6 Degrees of freedom adjustment of the light spot

In an early stage it was identified that the concept had two critical issues, which had to be solved in order to achieve a functional design of the adjustment mechanism. In order of importance these issues were:

- Due to the sliding contact between the body and the supports, friction will occur and may inhibit movement. (rolling friction was not considered as this would increase the number of mechanical interfaces).
- Coupling between the adjusted axes cannot be avoided, this may interfere with the necessity of an adjustment procedure with a limited number of iterations

The first critical issue was assumed to be avoidable by a proper placement of the supports, but no easy method was known to assess the functionality of the design. For this reason a new calculation method was developed. This method determines whether the adjusted body will move in all degrees of freedom, given a configuration of the support, an attachment point and a direction of the force holding the body onto the supports and the value of the friction coefficient.
A description of the method is given in the section 3.

The issue of coupling between the degrees of freedom was judged to be less critical. In similar adjustment problems it was found that a trained human operator can in many cases deal with some degree of coupling. However, in order to ascertain that this assumption was valid for the new design, tests would be required. In order to minimize the amount of hardware building a simulation method was developed that allowed seeing the interaction between the adjustment of the supports and the movement the operator sees on a monitor.
This simulation method is described in section 4.

3. ANALYSIS OF MOVEMENT OF THE ADJUSTED BODY

1. Approach of the analysis

The problem of how to determine whether the adjusted body will move over the supports as required is approached with the following steps:

- *Find how the body can move if one support is removed*

Assume the body will always stay in contact with the supports. When one support is removed, one degree of freedom is not restrained anymore. This degree of freedom will allow one specific combination of translation and rotation of the adjusted body. See Figure 3.

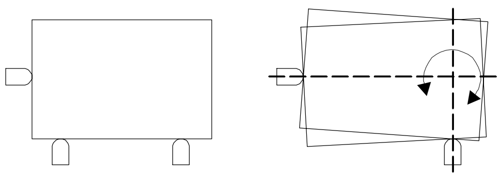

Figure 3 : The adjusted body can move according to one translation/rotation combination if one support is removed (2D case)

- *Determine direction of movement that moves the body in the direction of the force*

When a support is removed, the body can move according to the released degree of freedom in two directions. One of these directions will cause a movement of the attachment point of the force in the direction of the force. See Figure 4.

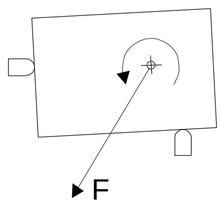

Figure 4: The presence of the force will move the body in one direction

- *Force and moment balance in friction-free situation under the assumption of continuous contact*

In the previous step it was determined how the body will move if it stays in contact with the five remaining supports. In this step it is taken as a starting point that this predicted movement will be followed, and it is calculated what forces between supports and body are necessary to ensure this. This is determined by solving the equations of force and moment balance for the case a support is retracted. The inertia forces have to be taken into account in order to achieve balance.
First the force and moment balances are calculated for the friction free situation. The resulting forces allow the following check:

- The forces that the supports exert on the body have to be positive. If not, it would mean that the support would have to pull the body in order to maintain contact. Since a support cannot exert a pulling force on the body, this means that the body will loose contact with the support.

- *Force and moment balance in friction-present situation under the assumption of movement*

In the friction-free situation it is known that the direction of the force that a support exerts on the body will be normal to the body. With friction, the force of the support on the body will have also have a lateral component. In order to assess this situation, the fact is used that it is known in what direction the body will move over the supports. The direction of the friction force will be exactly opposite. Concerning the value of the friction force, the force and moment balances are calculated under the assumption that the body moves (while maintaining contact with the supports). If this assumption is true, the friction force will be given by the product of the friction coefficient (f) and the normal force (to be exact: the static friction coefficient, since only if the static friction is exceeded the body will move). Thus the direction of the force of the supports on the body is known (still assuming that the body does move). See Figure 5.

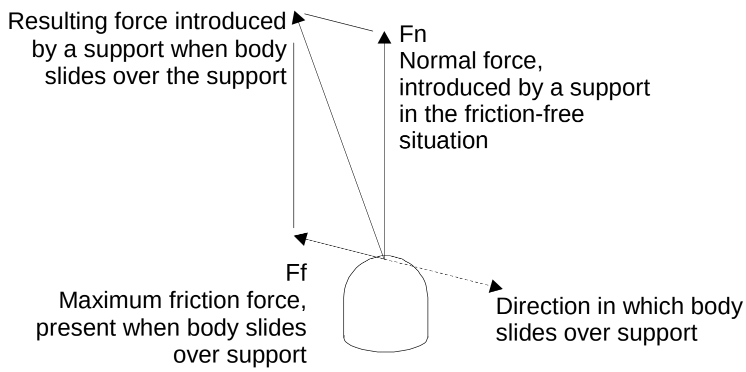

Figure 5: Forces introduced by a support on the adjusted body

The result of the calculation of the force and moment balances allows the following check:

- The direction of the reaction force has to be negative (i.e. opposed to the predicted direction of the movement). This should be the case since the inertia force is opposed to the direction of the acceleration. If it is positive the force and moment balance indicates that the body moves in the direction opposed to the pulling force! This is physically impossible, so it must be concluded that the assumption that the body moves is false.

This calculation is repeated for a retraction of each support. Per support a check on the sign of the reaction force shows whether a problem exists. If all reaction forces are negative, the adjusted body will move as designed.

2. The analysis

The analysis discusses the case in which the body rests on 3 z-supports (z1, z2 and z3), two y-supports (y1 and y2) and one x support (x1). Moreover, these supports are placed orthogonally with respect to each other (indicated by the names). This simplifies several steps of the analysis. However, the method of the analysis may also be used for other configurations.

- *Determine the movement of the adjusted body in case of a retracted support*

The analysis assesses what the displacements over the supports will be when one support is retracted. It is based on small displacements. In the first part of the analysis the body is taken as a reference frame, and it is calculated what movement of the frame holding the supports is possible while maintaining contact with the body.

It is known that movements over the x support will be in the yz plane, movements over the y-supports will be in the xz plane and movements over the z-supports will be in the xy plane.

Using this in the situation that the y1-support is removed leads to:

$$\begin{aligned}
\mathbf{v} + \mathbf{R}\cdot\mathbf{x1} &= \mathbf{x1} + [\;0 \quad dy(x1)_{y1} \quad dz(x1)_{y1}\;]^T \\
\mathbf{v} + \mathbf{R}\cdot\mathbf{y2} &= \mathbf{y2} + [\;dx(y2)_{y1} \quad 0 \quad dz(x1)_{y1}\;]^T \\
\mathbf{v} + \mathbf{R}\cdot\mathbf{z1} &= \mathbf{z1} + [\;dx(z1)_{y1} \quad dy(z1)_{y1} \quad 0\;]^T \\
\mathbf{v} + \mathbf{R}\cdot\mathbf{z2} &= \mathbf{z2} + [\;dx(z2)_{y1} \quad dy(z2)_{y1} \quad 0\;]^T \\
\mathbf{v} + \mathbf{R}\cdot\mathbf{z3} &= \mathbf{z3} + [\;dx(z3)_{y1} \quad dy(z3)_{y1} \quad 0\;]^T
\end{aligned}$$

Notation:
bold lowercase variables indicate (in most cases 3 component) vectors
bold capitals indicate matrices

with	**v**	translation vector of the frame holding the supports (with respect to a fixed but arbitrary reference co-ordinate system)
	R	rotation matrix defining the (3D) rotation of the frame holding the supports
	x1…z3	position vectors of the supports
	$da(b)_c$	the displacement in direction a of support b due to removal of support c

These are all vector equations, so the 5 equations represent 15 scalar equations.
The number of unknowns is: 3 components of **v**, 3 rotation-angles of **R** and 5x2=10 displacements, so 16 unknowns. This is one unknown to many, but since we are only interested in the direction of the movement, we can set one of the displacements $da(b)_c$ to a (small) value and than solve the system. Note that for specific cases a displacement may be zero, the variable indicating such a displacement should not be used to set to a finite value.

Based on small rotations, the rotation matrix is simplified to

$$\mathbf{R} = \begin{bmatrix} 1 & -c & b \\ c & 1 & -a \\ -b & a & 1 \end{bmatrix}$$

with	a	the rotation around the x-axis
	b	the rotation around the y-axis
	c	the rotation around the z-axis

For a fast solution of the system, the vector equations above have to be rebuild to one matrix-equation in which all unknowns are in one parametervector. Below it is shown how the first vector equation is rebuild.

$$\begin{bmatrix} 1 & 0 & 0 & \mathbf{x1}_1 & 0 & \mathbf{x1}_3 & \mathbf{-x1}_2 \\ 0 & 1 & 0 & \mathbf{x1}_2 & \mathbf{-x1}_3 & 0 & \mathbf{x1}_1 \\ 0 & 0 & 1 & \mathbf{x1}_3 & \mathbf{x1}_2 & \mathbf{-x1}_1 & 0 \end{bmatrix} \cdot \begin{bmatrix} \mathbf{v}_1 \\ \mathbf{v}_2 \\ \mathbf{v}_3 \\ 1 \\ a \\ b \\ c \end{bmatrix} = \begin{bmatrix} \mathbf{x1}_1 + 0 \\ \mathbf{x1}_2 + dy(x1)_{y1} \\ \mathbf{x1}_3 + dz(x1)_{y1} \end{bmatrix}$$

The subscript of a vector indicates the component (1 is x-direction, 2 is y-direction, 3 is z-direction).
There is still one known in the parametervector, and some unknowns are at the right of the equation sign. More reshuffling gives:

$$\begin{bmatrix} 1 & 0 & 0 & 0 & \mathbf{x1}_3 & \mathbf{-x1}_2 & 0 & 0 \\ 0 & 1 & 0 & \mathbf{-x1}_3 & 0 & \mathbf{x1}_1 & -1 & 0 \\ 0 & 0 & 1 & \mathbf{x1}_2 & \mathbf{-x1}_1 & 0 & 0 & -1 \end{bmatrix} \cdot \begin{bmatrix} \mathbf{v}_1 \\ \mathbf{v}_2 \\ \mathbf{v}_3 \\ a \\ b \\ c \\ dy(x1)_{y1} \\ dz(x1)_{y1} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

(If either $dy(x1)_{y1}$ or $dz(x1)_{y1}$ were chosen to serve as a set known, this term would not have been moved in the parametervector.)

For the whole system, the parametervector has to be extended. For the case where y1 is removed and, say, the movement along the y direction of support x is set as a known, the parameter becomes:

$$\mathbf{p} = [\mathbf{v}_1\ \mathbf{v}_2\ \mathbf{v}_3\ a\ b\ c\ dz(x1)_{y1}\ dx(y2)_{y1}\ dz(y2)_{y1}\ dx(z1)_{y1}\ dy(z1)_{y1}\ dx(z2)_{y1}\ dy(z2)_{y1}\ dx(z3)_{y1}\ dy(z3)_{y1}]^T$$

With the parametervector defined, it is possible to build the matrix equation that defines the whole system (once again for the case y1 is removed).
Some additional matrices are defined to make the matrix equation more compact:

$$\mathbf{I} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad \mathbf{T_1} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & 1 & 0 \end{bmatrix} \quad \mathbf{T_2} = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ -1 & 0 & 0 \end{bmatrix} \quad \mathbf{T_3} = \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

This results in

$$\begin{bmatrix} \mathbf{I} & \mathbf{T_1}\cdot\mathbf{x1} & \mathbf{T_2}\cdot\mathbf{x1} & \mathbf{T_3}\cdot\mathbf{x1} & \\ \mathbf{I} & \mathbf{T_1}\cdot\mathbf{y2} & \mathbf{T_2}\cdot\mathbf{y2} & \mathbf{T_3}\cdot\mathbf{y2} & \\ \mathbf{I} & \mathbf{T_1}\cdot\mathbf{z1} & \mathbf{T_2}\cdot\mathbf{z1} & \mathbf{T_3}\cdot\mathbf{z1} & \begin{bmatrix} \textit{submatrix} \end{bmatrix} \\ \mathbf{I} & \mathbf{T_1}\cdot\mathbf{z2} & \mathbf{T_2}\cdot\mathbf{z2} & \mathbf{T_3}\cdot\mathbf{z2} & \\ \mathbf{I} & \mathbf{T_1}\cdot\mathbf{z3} & \mathbf{T_2}\cdot\mathbf{z3} & \mathbf{T_3}\cdot\mathbf{z3} & \end{bmatrix} \cdot \mathbf{p} = \mathbf{0}$$

(the bold 0 indicates a vector with the same number of elements as **p**)

The submatrix contains mainly zeros. The terms differing from zero have to be defined for each case (removed support and variable that is given a set value). This is not elaborated.

The solution of the system can now be simply obtained by a mathematical program using matrix mathematics. This means **v** and **R** can now be found. This means the movement the frame (that holds the supports) can make is known with respect to the adjusted body. The movement of the body with respect to the frame with the support is simply the inverse of calculated movement.

- *Determine direction of movement that moves the body in the direction of the force*

Since the movement of the body is now known, it is simple to calculate how the attachment point of the force will move. Checking whether the component in the direction of the force is in the same direction as the force can be checked by calculation the dot product of the vector defining the direction of the force and the vector defining the movement of the attachment point. If the result is positive the attachment point moves in the direction of the force. If the result is negative the body moves against the force, and the direction of the movement has to be corrected.

- *Force and moment balance in friction-free situation*

It is now known how the body will accelerate (both translation and rotation) when a support is retracted. Hence it is possible to calculate the forces when the body is starting to accelerate. This is done by solving the force and moment balance, where the presence of the inertia and moment of inertia has to be included.
The force and moment balance represent 6 equations, while the five supports (one support is retracted) introduce 5 normal forces and the inertia introduces 3 force-components and 3 moment-components, meaning a total of 11 variables have to be found. The number of equations seems to be far to low.
However, in the previous steps it has been determined in what combination of translation and rotation the body will be subjected to as soon as a support is removed. So instead of three force components there is just the magnitude of the force that is unknown. Similarly instead of three moment components only the magnitude of the moment is unknown (without proof: the rotation axis is given by $[\ a\ \ b\ \ c]^T$, the angle of rotation is given by $\mathrm{sqrt}(a^2+b^2+c^2)$). Finally the relation between rotation and translation is known, so the ratio between inertia-moment and inertia-force can be found. The latter is feasible because it is known what the rotation α and the translation s of the body are at a given time t. Hence the equations $s=0.5\cdot(Fi/m)\cdot t^2$ (with m the mass of the body and Fi the reaction force) and $\alpha=0.5\cdot(Mi/I)\cdot t^2$ (with I the moment of inertia of the body and Mi the reaction moment of inertia) can be combined to find:

$$Mi = I/m \cdot \alpha/s \cdot Fi$$

Both the reaction force and the reaction moment act in the center of gravity of the body, so the translation s and the rotation α of this point have to be used. The rotation of all points in the body is equal, so this does not require a new calculation, the translation for the center of gravity can be found using the translation vector **v** and the rotation matrix **R** found before, according to

$$\mathbf{w}_{cg} = (\mathbf{R}^T\cdot\mathbf{cg}-\mathbf{v}) - \mathbf{cg}$$
$$\mathbf{u}_{cg} = \mathbf{w}_{cg} / ||\mathbf{w}_{cg}||$$

(the $\mathbf{R}^T\cdot\mathbf{cg}\text{-}\mathbf{v}$ is the inverse transformation, because the frame is fixed and the body is moving)

with $\mathbf{w}_{cg}$ vector giving the translation of the center of gravity
$\mathbf{cg}$ vector giving the (initial) position of the center of gravity of the body
$\mathbf{u}_{cg}$ normalized vector in the direction in which the center of gravity moves

Here a normalized vector is for the first time calculated. This will be repeated several times because the use of normalized vectors allows to introduce only the magnitude (of the force or the moment) as a variable.

After these preparations it is possible to solve the force and moment balances

$$\Sigma\mathbf{F} = \mathbf{0}$$
$$\Sigma\mathbf{M} = \mathbf{0}$$

This holds for the x-, y- and z-directions, so this represents 6 equations.

In case y1 is retracted, the unknowns are
Fx1, Fy2, Fz1, Fz2, Fz3, Fi
where Fi is the value of the inertia force.
Note: all unknowns are scalars, because directions and attachment points are known.

The summations for the force balance can be expanded to yield

$$\mathbf{ux1}_1\cdot Fx1 + \mathbf{uy2}_1\cdot Fy2 + \mathbf{uz1}_1\cdot Fz1 + \mathbf{uz2}_1\cdot Fz2 + \mathbf{uz3}_1\cdot Fz3 + \mathbf{ucg\_y1}_1\cdot Fi + \mathbf{upf}_1\cdot Fpf = 0$$
$$\mathbf{ux1}_2\cdot Fx1 + \mathbf{uy2}_2\cdot Fy2 + \mathbf{uz1}_2\cdot Fz1 + \mathbf{uz2}_2\cdot Fz2 + \mathbf{uz3}_2\cdot Fz3 + \mathbf{ucg\_y1}_2\cdot Fi + \mathbf{upf}_2\cdot Fpf = 0$$
$$\mathbf{ux1}_3\cdot Fx1 + \mathbf{uy2}_3\cdot Fy2 + \mathbf{uz1}_3\cdot Fz1 + \mathbf{uz2}_3\cdot Fz2 + \mathbf{uz3}_3\cdot Fz3 + \mathbf{ucg\_y1}_3\cdot Fi + \mathbf{upf}_3\cdot Fpf = 0$$

with	**ua**	unit vector giving the direction of the force introduced by support a
	Fa	value of the force introduced by support a
	ucg_y1	unit vector indicating the direction in which the body will move if support y1 is retracted
	upf	unit vector indicating the direction of the force pulling the body towards the supports (pf = pulling force)
	Fpf	value of the pulling force (known)

The moment balance can be written out by the introduction of 'unit momentvectors'. These 'unit momentvectors' have to be multiplied with a scalar representing the value of the moment in order to get the traditional momentvector. How this unit momentvector can be calculated can be seen by the following deriviation:

- The momentvector is given by the crossproduct of the lever arm and the force: **M** = **F** x **a**
  (x indicating a cross product, in this case **M** and **F** indicate vectors)
- In this relation, the force vector can be written as a scalar times a unit vector: **M** = (F·**u**) x **a**
- Using associativity, this can be written as: **M** = F· (**u** x **a**)
- And this suggests the introduction of the unit momentvector **m** = (**u** x **a**), which means: **M** = F· **m**

$$\mathbf{mx1}_1\cdot Fx1 - \mathbf{my2}_1\cdot Fy2 + \mathbf{mz1}_1\cdot Fz1 + \mathbf{mz2}_1\cdot Fz2 + \mathbf{mz3}_1\cdot Fz3 + \mathbf{mcg\_y1}_1\cdot Fi + \mathbf{mpf}_1\cdot Fpf = 0$$
$$\mathbf{mx1}_2\cdot Fx1 - \mathbf{my2}_2\cdot Fy2 + \mathbf{mz1}_2\cdot Fz1 + \mathbf{mz2}_2\cdot Fz2 + \mathbf{mz3}_2\cdot Fz3 + \mathbf{mcg\_y1}_2\cdot Fi + \mathbf{mpf}_2\cdot Fpf = 0$$
$$\mathbf{mx1}_3\cdot Fx1 - \mathbf{my2}_3\cdot Fy2 + \mathbf{mz1}_3\cdot Fz1 + \mathbf{mz2}_3\cdot Fz2 + \mathbf{mz3}_3\cdot Fz3 + \mathbf{mcg\_y1}_3\cdot Fi + \mathbf{mpf}_3\cdot Fpf = 0$$

with	**ma**	unit vector giving the direction of the moment introduced by support a
	$\mathbf{ma}_n$	nth component of vector **ma** (1 is x-direction, 2 is y-direction, 3 is z-direction)
	Fa	value of the force introduced by support a
	mcg_y1	unit vector indicating the direction of the inertia moment vector of the body if support y1 is retracted
	mpf	unit vector indicating the direction of the moment introduced by the pulling force
	Fpf	value of the pulling force (known)

The force and moment balance can be combined in one matrix equation:

$$\mathbf{B} \cdot \mathbf{p_F} = \mathbf{y}$$

with	**B**	matrix holding all the coefficients of the parametervector $\mathbf{p_F}$
	$\mathbf{p_F}$	parametervector, in this case [Fx1, Fy1, Fz1, Fz2, Fz3, Fi]
	y	vector holding the (negated) terms with Fpf

Assembly of **B** and **y** is straightforward.

Once again, a mathematical program can solve this matrix equation, thus yielding the forces on all unknown forces. Note: given an unfortunate configuration it is possible that even in this friction-free situation the reaction force is negative or any of the forces introduced by the supports is negative. Study of the results of the calculation will reveal such situations.

- *Force and moment balance in friction-present situation*

As stated in the previous section, assessment of the design in the case of friction can be performed by assuming that the direction of the forces introduced by the supports is given by the sum of the normal force and the maximum value of the friction force. A situation in which movement of the body would be inhibited by friction than shows up as a positive reaction force, while with a functional design the reaction force will be negative.
Because it is known in which direction the body tends to slide over the support, the direction of the friction force is know and the unit vector giving the direction of the sum of normal and friction force can also be determined.
This is done by first calculating how the point, initially in contact with the support, is moved:

$$\mathbf{v_{x1}} = (\mathbf{R^T} \cdot \mathbf{x1} - \mathbf{v}) - \mathbf{x1}$$
$$\mathbf{t_{x1}} = \mathbf{v_{x1}} / \|\mathbf{v_{x1}}\|$$

Then the direction vector follows by:

$$\mathbf{ux1_f} = (\mathbf{ux1} - \mu \cdot \mathbf{t_{x1}}) / \|\mathbf{ux1} - \mu \cdot \mathbf{t_{x1}}\|$$

(minus sign because the direction of the force is opposed to the movement direction)

Now the matrix **B** can be assembled in exactly the same way as previously, but the unit vectors for force and moment direction in the case of friction have to be used.
Solving the matrix equation once again results in a set of forces and a reaction force, and study of these results quickly shows whether friction will inhibit the movement.

3. Example of a calculation

The analysis presented above has been implemented in a matlab script. This script calculates the forces for retraction of all supports sequentially.
Below an output of the script is shown for a configuration where several things go wrong.

```
Forces in the friction-free situation
First row: inertia force in the direction towards retracted support
 (should be negative, otherwise friction would cause movement instead of stopping it)
Following five rows: forces on the not-retracted supports
 (should be positive, otherwise the support would pull)
Pattern
   *Fx1*     *Fy1*     *Fy2*     *Fz1*     *Fz2*     *Fz3*
    Fy1       Fx1       Fx1       Fx1       Fx1       Fx1
    Fy2       Fy2       Fy1       Fy1       Fy1       Fy1
    Fz1       Fz1       Fz1       Fy2       Fy2       Fy2
    Fz2       Fz2       Fz2       Fz2       Fz1       Fz1
    Fy3       Fz3       Fz3       Fz3       Fz3       Fz2

  -20.0000   -5.9985   -2.4631   -0.8594   -0.0636   -2.0721
   13.8944   14.9696   22.0009   19.3951   19.9552   20.0000
   26.1056   36.7324   38.5635   28.1082   28.4843   28.4683
   10.9848   13.4637   14.5690   11.9574   11.5108   11.4242
    2.1826   -0.1816   -1.3512    0.4988   14.1053   24.1017
   21.8326   21.7179   21.7822   33.8943   20.9397    8.8289

Forces in the friction-present situation

   -5.0000   -4.2921    0.6180   -0.4927    0.3239   -0.2140
   17.9861    4.0505   30.6573    8.8869    9.9532   20.3961
   22.8061   34.5127   29.5254   22.9290   24.0426   29.0280
   10.3425   11.1132   17.3571   17.3524   18.0088   15.5011
    3.0856    2.2286   -2.7241    3.8236   10.2104   19.3616
   22.2650   22.3513   21.0601   34.4644   23.6354    3.2008
```

Study of the results shows that the attachment point and the direction of the pulling force have been chosen wrong, even in the friction-free situation. The negative signs of the force on support z2 in case of retraction of supports y1 and y2 (in bold in the friction-free situation) show that in these cases the body is lifted of support z2.
In case of the situation with friction, the friction seems to aid in the case that y1 is retracted. However, starting with a situation that does not function in a friction free situation is fundamentally wrong (in other words, we do not have to look to the friction present results at all, it is done here only as an example).
In the case of retraction of z2 (in bold in the friction-present situation) the classical problem with this adjustment concept is visible: in the friction-free situation the mechanism works as expected, but when friction is present the positive value of the reaction force shows that a problem exist. In practice this means that friction will inhibit movement of the body in case support z2 is retracted.
Finally in case of retraction of support y2 (gray column) it is indicated that (in the presence of friction) the body is still lifted of support z2, while the positive value of the reaction force indicates that friction inhibits movement. In this case the analysis does not represent a realistic situation anymore. This is a consequence of starting with a situation that is incorrect in the friction-free situation.

4. Validation of the analysis

The analysis presented above has been used to aid in the design of (presently) six different adjustment mechanisms and kinematic mounts, among which the adjustment of the light spot which is the subject of this paper. In all cases the value of the friction coefficient was determined by experiment.

In all cases the adjustment mechanism worked directly as intended the first time.

Hence, the analysis has shown to be a successful aid in the design of the type of adjustments in which a body is pulled on six adjustable supports.

Figure 6 shows an image of the adjustment as implemented for adjusting the light spot of the calibration sensor. In the analysis it was shown that this configuration should function with friction coefficients up to 0.3. In experiments with the material combination a friction coefficient of about 0.12 was found. Presently in the order of 100 of these adjustments have been made and found to function without exception.

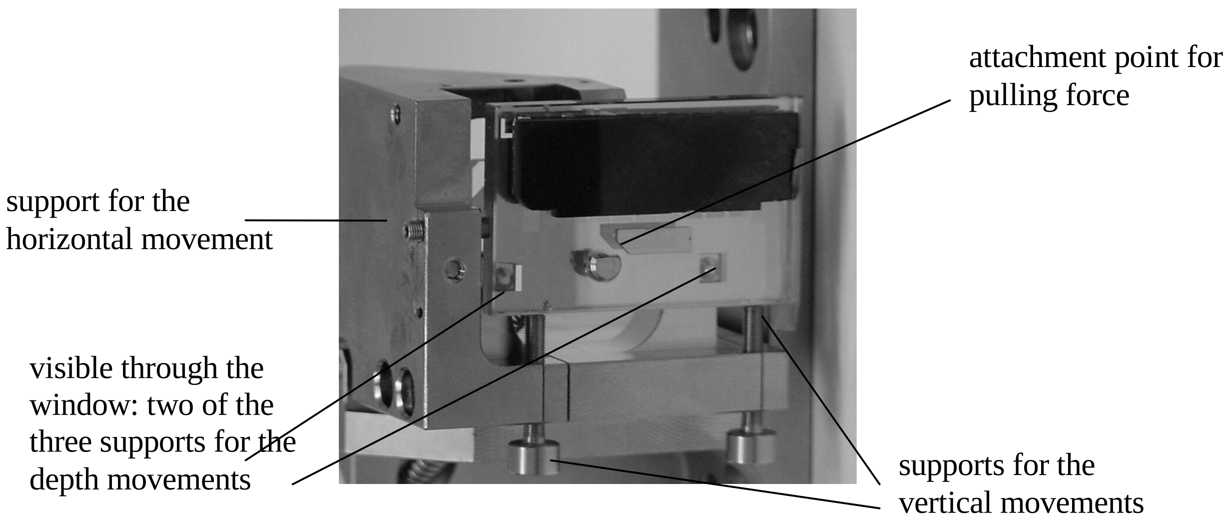

Figure 6: Hardware of the adjustment mechanism as described, in analysis it was shown the mechanism should function with friction coefficients up to 0.3

4. SIMULATION OF INTERACTION BETWEEN ADJUSTMENT AND IMAGE MOVEMENT

The previous section was dedicated to an analysis to aid realizing an adjustment that would move in all required degrees of freedom.
This section is dedicated to how an operator can achieve the optical aim with the adjustment procedure as designed.

This problem does require attention, because the chosen mechanical concept introduces coupling between axes, as indicated in Figure 7. No configuration of support placements can avoid the existence of coupling.

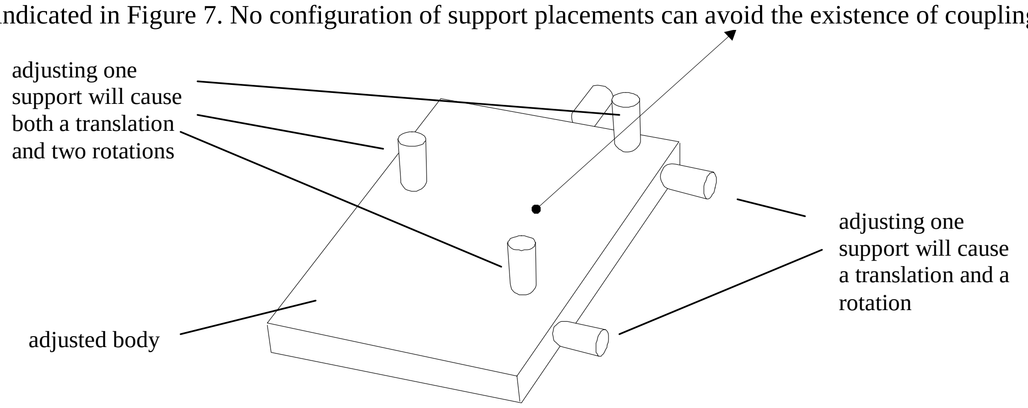

Figure 7 : Coupling of axes in the adjustment

However, the existence of coupling between the axes does not by definition cause a difficult adjustment procedure. In the design the following helps us:

- A human operator is quite capable of dealing with some coupling between adjusted axes
- By proper choice of support position the poles of the movement (point around which the movement seems to rotate) can be made to coincide with marker points for the operator.

In this way the adjustment procedure may turn out to be relatively simple. True as this statement may be, it is still preferable to check the feasibility of the adjustment prior to the building of hardware. A simulation of the interaction between the actions of the operator (an adjustment of a support) and the effect of the system output (e.g. change in a monitor image) can serve to show in an early stage whether a mechanical configuration of the adjustment, the tool that visualizes the output of the system and the adjustment procedure allows a successful alignment of the system.
The realization of such a system can easily be based on the model that was developed to assess the influence of friction.
The model already allows the calculation of the exact movements of the adjusted body for a movement of any support. The transformations describing the movements can easily be performed on any point on the moving body, and thus show the movement of this point.
In the case of the calibration sensor, this method was used to simulate the monitor image of the two marker lines that had to be aligned with a horizontal line present in the receiving optics, as shown in Figure 8. This figure shows the screen of the simulation. Apart from the monitor image, six scroll bars are visible that simulate the six adjustments. If a scroll bar is moved, the monitor image changes in the way it would in the final adjustment mechanism with visualization tool. A combined widening and loss of contrast of the marker image in this case indicate the defocus of the image.
Using this simulation, the feasibility of the adjustment was shown while the design was still in concept phase.

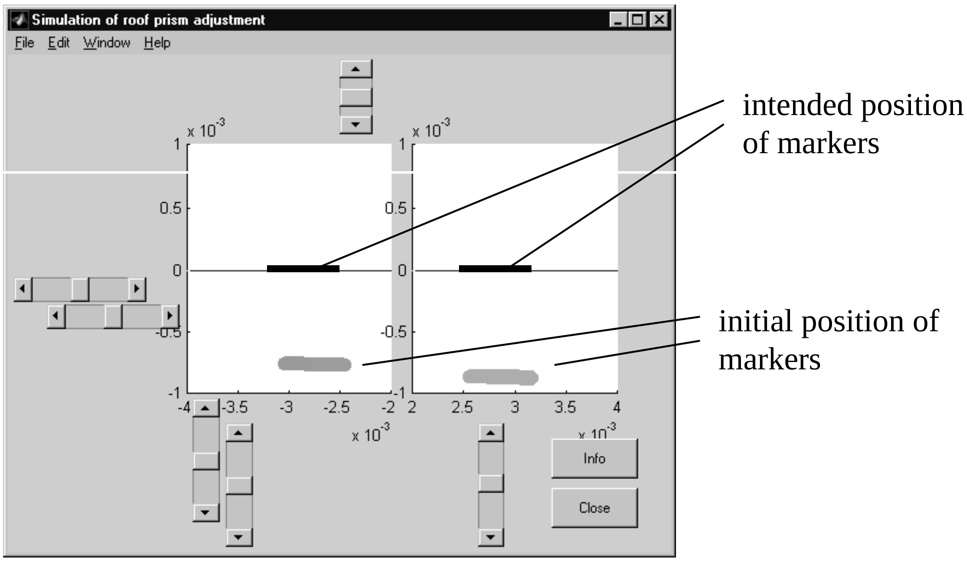

Figure 8: Screen of a simulation of the interaction of adjustment and image on the monitor

5. CONCLUSIONS

A method has been developed to quickly analyze whether friction will interfere with the proper functioning of an adjustment mechanism based on a body pulled onto six adjustable supports.
The method is provisionally validated, as it has successfully aided the development of several adjustment mechanisms based on this principle.

The method also potentially allows aiding a designer in the improvement of a configuration. Such a feature is presently not implemented in the analysis.

The mathematics developed for the above analysis has also been used to facilitate a simulation of the interaction between operator, adjustment mechanics and visualization tool in order to show the feasibility of the adjustment in the concept stadium of the design.

ACKNOWLEDGEMENTS

Although the development of the mathematics is mostly a one-person business, the development of the mechanism is a team effort. From the team I want to mention specifically Sander Struijcken, who designed vital elements like the fine-threaded screw to drive the adjustment and the locking that guaranteed that a 1 um adjustment wasn't lost when the system was locked. I also want to thank Marc Hoppenbrouwers, who performed a thorough check of the mathematics.

REFERENCES

1. Rubingh et al, ‘*Performance of a high-productivity 300-mm dual-stage 193-nm 0.75-NA TWINSCAN AT:1100B system for 100-nm applications*’, SPIE proceedings vol 4691, page 696.
2. Pollard, A. F. C., *The Kinematical Design of Couplings in Instrument Mechanisms*, London: Adam Hilger, 1929
3. Blanding, D.L, *Principles of Exact Constraint Mechanical Design*, Eastman Kodak Co., Rochester, NY 14650, 1992
4. Koster, M.P., Constructieprincipes voor het Nauwkeurig Bewegen en Positioneren, Twente University Press, 2000 (in Dutch)