# 88320 CALIBRATIONS
# FOR HEXAPODE CMW

**François WILDENBERG**

*CMW*
*43, Avenue du Général Leclerc*
*F.88320 Rozières-sur-Mouzon*
*hexapode.cmw@wanadoo.fr*

*ABSTRACT: In order to manufacture a machine tool based on the Hexapod mechanism, the designer has to address a various of theoretical problems (design, calibration and control) and also several practical difficulties which increase the theoretical burden. Thus, CMW is developing the Hexapod CMW-300. Through its unique design experience, CMW introduces here several difficulties which were rarely studied by scientists. The typical encountered difficulties which are mainly to: manufacture an Hexapod according to plans, make significant measures, perform useful calibration, take unexpected loads into account, achieve accurate trajectory tracking. Inasmuch as the Hexapod is not a pure parallel mechanism, CMW introduces a complete technical strategy in order to solve the identified problems.*

*KEYWORDS: Hexapod, Calibration, High speed machining.*

## INTRODUCTION

**1) To build an hexapod, it is quite easy**

First, you take 6 car ball joints, then 6 commercial cylinders, 2 plywoods a few screws and then you get an hexapod. You have a robot that moves well. You can be proud and satisfied.

**2) To build an hexapod fitted for industrial use is quite difficult**

There are 2 problem types:

1° Theoretical difficulties for manufacturing and control.
2° Practical difficulties to manufacturing.

**3) There are many false ideas about Hexapods**

1° The Hexapod is a parallel mechanism: it's wrong.
2° The Hexapod is very economical: it's wrong.
3° The Hexapod is easy to calibrate: it's wrong.
4° The Hexapod can be developed by a large company: it's wrong.
Now the manufacturing practice of an Hexapod shall be exposed.

**4) The Hexapod holds the problems of serial and parallel architectures**

1° As a matter of facts, an Hexapod is a mix of parallel and serial structures. Hence, in-between articulations, the architecture is serial where you find the greatest number of mechanical pieces.
Although, the architecture is globally parallel.
2° Any parallel mechanism is not linear and is not isotropic.

This means that:

a) at one workspace point, defect errors can yield negligible impacts and at another they can yield significant impacts,
b) between the two points, the incidence shall not evolve linearly,
c) the prediction law is complex, so one axis defect can be subdued and another axis defect can be amplified,
d) the defect addition is hardly predictable, thus, it is often impossible to order them in a significant hierarchy.

# I. The difficulties

**1) Manufacturing conformity**

***11) Any mechanical machine is always wrongly built***

Scientists are not aware of that; draftsmen neither; but I know it since my expertise is milling.

Year round, CMW welds, machines, assembles from clients' drawings. Thus, we manufacture precision mechanical systems.

- Year round, we do manufacture faulty parts. Hence, any part is never done to drawing references, this is the rationale behind drawing tolerances (length, perpendicularly, parallelism, etc),
- Year round, we do receive drawings with impossible accuracy requirements. Hence, for the draftsman, it is quite easy to mark any tolerances on drawings but, for the manufacturer, it is another story to build.
- What is generally true for mechanical structures is also true for any Hexapod. Henceforward, an Hexapod shall always be manufactured wrong, even though is drawn exact.

***12) A little inventory of common fabrication errors***

Scientists have addressed the manufacturing problems in articles such as [WAN 93].

CMW has experienced several manufacturing difficulties which are explained in the following.

A) The ball screw :

- The ball screw nut reference is never parallel to the ball bearing way **(figure 1)**

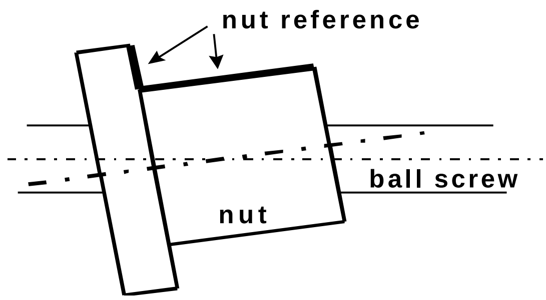


**figure 1**: *Nut reference axis alignment.*

**-** The nut reference axis is never concentric with the ball bearing way. There is an offset between axes **(figure 2).**

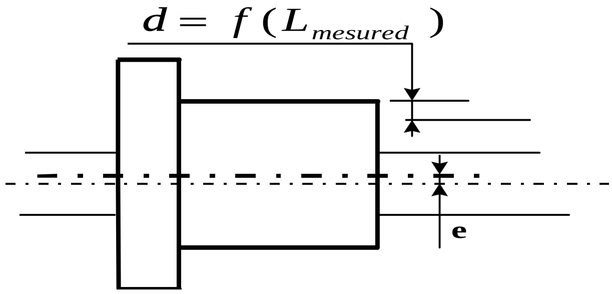


**figure 2**: *Nut reference axis offset.*

**-** The ball screw fixture bearing axes are not parallel to the ball screw centre line.

**-** The ruler axis is actually not parallel to the ball screw axes and suffers a slight offset **(figure 3)**.

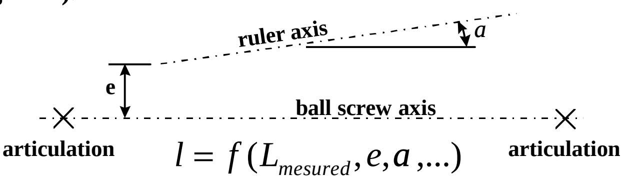


**figure 3**: *Ruler axis alignment.*

B) The linear guiding frame:

On one side, the guiding frame is fixed on the ball screw nut. On the other side, it is fixed on the leg skeleton.

It should be parallel to the ball screw bearing way.

C) Articulations:

There are 2 articulation types:

**-** universal joints,

**-** ball joints.

- Ball joint articulation:

This looks the simplest but:

**-** it is mandatory that the leg axis crosses the ball centre. If it is not the case (it is never the case!), then it shall be impossible to implement angle correction along the leg axis **(figure 4).**

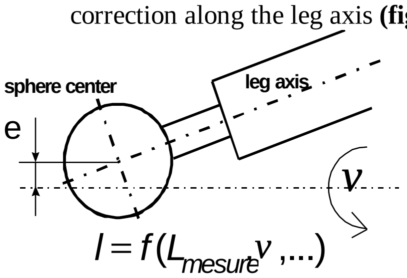


**Figure 4 :** *Ball joint alignement.*

It is mandatory that the articulation housing and ball be concentric, otherwise there will be mounting problems **(figure 5).**

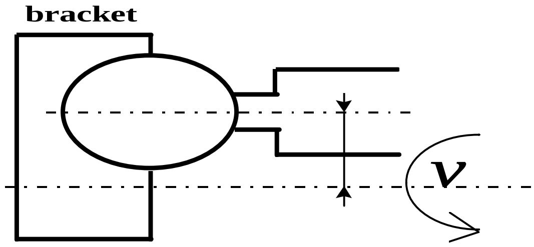


**Figure 5 :**
*Ball joint offset.*

$$l = f(L_{mesured}, v, \ldots)$$

- Articulation type universal joint **(figure 5)**:
  - The ball joint fork axes are not aligned.
  - The ball joint fork axes are intersecting the main bar axis.
  - The bearing width tolerance is often higher than 100µm. A perfect piece is thus spoiled by improper mounting.
  - The ball joint fork axes are not perpendicular to the main bar axis.
  - The ball joint fork axes do not cross the articulation centre.

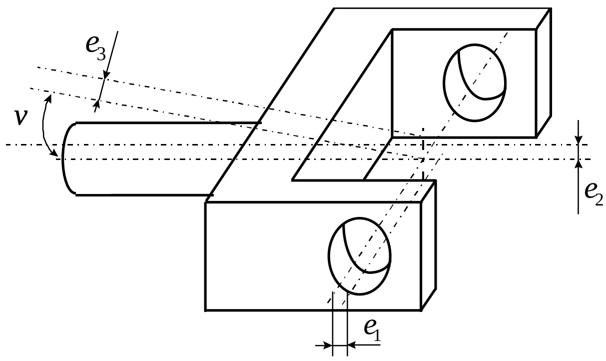


**Figure 6 :**
*Joint fork position.*

$$l = f(e_1, e_2, e_3, v, L_{mesured}, \ldots)$$

**2) Measurement difficulties**

***21) There exists a great number of measurement means***

Translation measurement:
- laser
- rulers

Angular measurement:
- laser
- encoders

The difficulties are identical.

***22) Let's take an example: the rulers***

- In-between articulations, theoretical centre – to - centre distance equals K plus ruler measured length.
- In practice, the real distance is a function of the above plus other parameters.

Thus, we have:

A) Sensor measurement (Micro-ruler lengths or encoder angles).

Observation:
All measuring devices are inaccurate to a certain degree. Any serious sensor manufacturer supplies calibration curves which are more or less false.
Solution
Evaluate calibration curve validity, implement calibration procedures for each measuring mean.
Remark
For each leg, 4 measuring means are supplied; this brings up to 24 calibrations on CMW' s Hexapod.
B) Micro-ruler and axis displacement parallelism
Observation:
Micro-rulers installation requires that the head-to-ruler distance be within tolerances. Furthermore, great care should be applied in order to make sure that the ruler does not move transversely.
Solution:
Set the distance between the measuring head and the micro-ruler with very high accuracy.
Remark:
Featured tolerances by micro-ruler manufacturers are much too high.
C) Micro-ruler and articulation centre line parallelism
Observation:
Micro-rulers are not installed parallel to the leg articulation centre lines. This comes from the fact that the articulation and the leg are imperfect.
A multitude of errors are possible; here are the most common:

**3) Calibration difficulties**

There exists a great number of defects. Calibration is undergoing theoretical and practical difficulties.

***31) First series of difficulties: any measurement is always false***

- This is obvious for the physicist,
  this is obvious for the mechanics,
  this is not tolerable for the mathematician and asks:
  "how can we calibrate when the measures are inexact?"
- The measure errors are caused by:
  the required accuracies: the µm is quite small on a 1200mm scale, thus measurement accuracies around 0.1 µm would be needed.
  - It is difficult to evaluate the ball screw axis.
  - It is difficult to evaluate an articulation centre position.
  - the mechanical structure suffers elastic deformation and measurements are somewhat unreliable.
  - A temperature change of 1°C introduces a lag error of 12 µ.

***32) Second series of difficulties: sensor multiplicity***

For each leg, 4 measuring means are supplied; this brings up to 24 calibrations on CMW' s hexapod.

***33) Third series of difficulties: classical calibration means are uneffective***

Classical [calibration] techniques are not effective since they are based.
1° On the direct geometric model which is unstable for parallel robots.

2° On platform position and orientation measurements. Geometric parameter errors have little influence on platform positioning, thus measurement errors shall lead to very negative impacts on calibration results. Vischer has given an empirical rule [VIS 98] which states that in order to improve knowledge of the articulation positions by 1/10, it is necessary to measure the platform position at the 1/100 magnitude.

Other calibration methods are possible where more than six sensors are used and where constraints have to be established on the Hexapod (example: one leg is moved along one fixed direction through the use of one external mechanism).

***34) Difficulties due to distortions***

Distortions are somewhat difficult to measure in-line. It is thus possible to install more sensors (strain gauges, thermometers, etc) but this can yield reliability problems and geometric model reconstruction can become complex.

Any mechanical structure is not infinitely rigid. Thus, here are some distortion causes:

A) the mobile platform shall distort under the following:
- the cutting forces,
- the gyroscopic forces,
- inertial forces during accelerations and breaking,
- leg actuation forces,
- temperature variation (10 µm / °C / meter).

B) the base shall distort under:
- leg actuation forces,
- leg transmitted forces and torques,
- support distortions,
- temperature variation.

C) the articulations shall distort under:
- …

D) the leg shall distort under:
- the articulation forces,
- the articulation torques,
- …

***35) Difficulties due to unexpected loads***

A) Everyone believes that, between articulations, the legs are only working in traction and compression: this is false.

There are radial forces because of the following:
- leg inertia,
- assembly defect residual strains,
- pre-stresses.

B) The construction pre-stresses build several forces.

Moreover, pre-stresses are difficult to measure.

During maintenance, pre-stress applications can lead to significant dimension changes.

***36) Difficulties for trajectory tracking***

After you have completed a so-called perfect Hexapod, you are now faced with trajectory tracking problems.

1° Control system cycle rate (response time frequency) Hexapod mechanisms are very fast machines which require a good amount of computations in a very limited amount of time. When milling feedrates are up to 18 m/min, you are travelling 0,3mm in 1 ms. Hence, in order to achieve high accuracy trajectory tracking, the control system shall act 10 times during one millisecond and that as to be done for each leg.

2° Direct Geometric Model convergence

Tool position X, Y, Z → IGM → Legs length (L1…L6)

Legs length (L1…L6) → DGM → Tool positions X, Y, Z

The inverse geometric model (IGM) is explicit and easy to com

In order to achieve Hexapod control with high accuracy, it is mandatory to use the direct geometric model (DGM) in the servo loop. The DGM is an iterative model as proposed in [MER 97]. But, the DGM yields up to 40 independent solutions and has been exactly studied for various types of Hexapods (MSSM, TSSM, SSM or general 6-6) in [ROL 99]. An exact model has been proposed to help tune the numerical one which is used in the iterative model. It can converge towards the needed solution or any other. It is also possible to see the system to jump from one trajectory to a nearby one.

How can the manufacturer insure that the Hexapod shall follow the right trajectory.

Hence, let two circles of radius R1 and R2, there are two solutions S1 and S2 to the two equation system.

An Hexapod is modelled by 6 intersecting spheres of radius L1, L2, L3, L4, L5 et L6 and has 36 solutions to the six equation system.

At time t=0, your Hexapod is located against the mechanical limits. You do know where it is and you do know which choice to make among the 36 SSM Hexapod solutions. At time t=0 … t=n, each solution follows its own trajectory. As the control system computations are iterative in nature, this leads to the possibility that you jump from one trajectory to another. Your Hexapod can suddenly move at high speed to unexpected and unplanned positions. To the worst, you can kill an operator or destroy equipment **(Figure 7).**

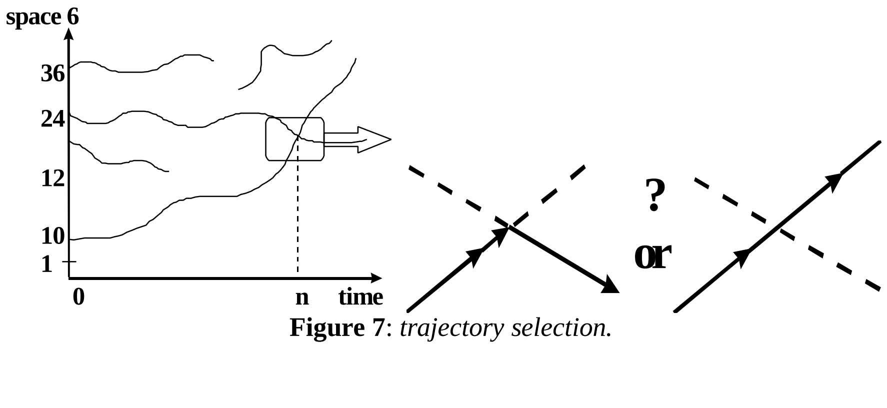


**Figure 7**: *trajectory selection.*

3° Spin angle F choice

The Hexapod includes 6 legs, hence 6 degrees of freedom (dof); the machine is used to perform 5 axis milling. One dof seems to be useless and there is an infinite number of solutions to reach any point (Imagine that you position the tool at one point, then you make the platform turn around the tool axis, this angle is simply the spin angle F ).

Some positions are physically impossible since:

- the legs would cross
- the actuators would hit the mechanical stops,
- the leg spans would be insufficient.

The remaining number of solutions would be the set of possible solutions which is still infinite.

It is thus necessary in each point to define an algorithm which chooses the optimised solution for:

- the most accurate Hexapod,
- the most rigid Hexapod,
- the fastest Hexapod,
- the lowest energy or torque requirements,
- the most realistic leg length variation.

4° Trajectory planning

Before the Hexapod is launched into a task, it is necessary to properly select a trajectory off-line which:

- stays inside the workspace,
- is compatible with the actuator extrema,
- is insuring required accuracy.

First, this means selecting a compatible meshnet. Then, this planning shall be done according to required accuracy, dynamic characteristics and geometric dimensions of the various Hexapod components.

# II. Proposed strategy:

1) Make inventory of all defects even the smallest,
2) Try to solve them, one by one, everything done is important progress,
3) Use partial calibrations,
4) Use pre-stressed mechanical systems in order to eliminate play, (fabrication errors, that’s enough!),
5) Use systems without wear in order to get stable calibrations in time, this also means to allow for system over-design,
6) At the design stage, foresee all maintenance requirements; for example, provide information on how to change any bearing after three years,
7) All parts shall be designed by finite-element methods. Warning: a highly rigid platform will be heavy thus it will flex the legs. The best platform may be not the most rigid.
8) Measure articulation angles to correct micro-rulers measurement.
9) Install articulation with a certain angle to optimise accuracy.

10) Follow carefully the temperature. It is quite complex to evaluate the distortions caused by temperature.
11) Use a very fast controller in order to make a maximum number of real-time computations.
12) Develop a appropriate CHAM (Hexapod dedicated CAM) which allows for a maximum number of computations off-line at the engineering stage.
13) Optimise the Hexapod geometry to improve accuracy and rigidity.
14) Calibrate the Hexapod in order to the support mounting errors.
15) Auto-calibrate the Hexapod: 4 measurement per leg in order to improve accuracy.
16) Measure all sub-assemblies before construction and integrate the correction factors in the various softwares.
17) Use adaptive PID control parameters in order to contract rigidity variations.
18) Use a mechanical balancer to minimise and centre forces.
19) Calibrate your internal measuring means in order to make sure thy are in line with international standards.
20) Record information about any piece done in order to be able to modify calibration during maintenance.
21) …

# CONCLUSION :

1) Conclusions are temporary. For the last 50 years, there has been improvements on cars; then, in the next 50 coming years, there shall yearly improvements on Hexapods.
2) The Hexapod shall not be a CONCEPT-CAR; it must do chips!
3) So many Hexapods are dramatically dangerous, since The manufacturer cannot exactly guarantee or insure that:

A) there are no singularities within the workspace.
B) the Hexapod shall follow the right trajectory.

4) An Hexapod is a terribly complex device.
5) The only way out: a co-operation between industry and research.
6) Several research programs are under way and many others are needed.

…

# REFERENCES

[MER 97] MERLET, J..P., *Les robots parallèles*, second edition, Paris, Hermes, 1997.

[VIS 98] VISCHER, P., and CLAVEL, R., "Kinematic calibration of the parallel Delta robot", In the journal Robotica, vol.16, n.2, pp.207-218, 1998.

[WAN 93] WANG, J., and MASORY,O., "On the accuracy of a Stewart Platform, Part I: the effect of manufacturing tolerances", In IEEE Int. Conf. on Robotics and Automation, Atlanta, pp.114-120, May 2-6 1993.