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INPLANT – A NOVEL 3D COORDINATE MEASURING SYSTEM FOR HOSTILE ENVIRONMENTS

Summary

- Goals
- The concept
- The design and prototype realisation
- Validation
- Conclusions

The work package 1: Innovative measurement systems

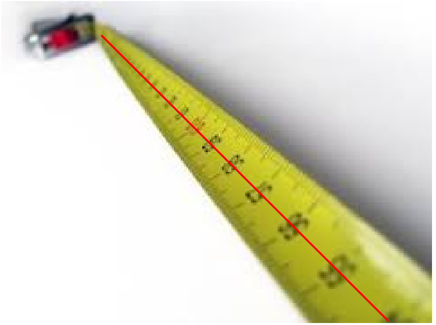
- Goal
  - *To deliver innovative systems operating over a volume of $(10 \times 10 \times 5)\ m^3$, to a target accuracy of 50 µm, in industrial environments*
- Two systems have been produced (prototypes)
  - **InPlanT, *Intersecting Planes Technique*** (INRIM)
  - **FSI, *Wide-beam Frequency Scanning Interferometry*** (NPL)

Optical instruments are popular

- For large dimensions, optical instruments seem to be an obvious choice. In fact the light
  - Has got no mass, and can be moved (redirected) easily over large distances
  - Travels (almost) straight
  - Travels any (indoor) distance
  - It is capable of carrying interferometric information

Two ways for using the light

- The light can be used to measure coordinates in two fundamental ways:
  - As a(n interferometric) distance meter
  - As a pointing device



Influence of the air on light: the refractive index, *n*

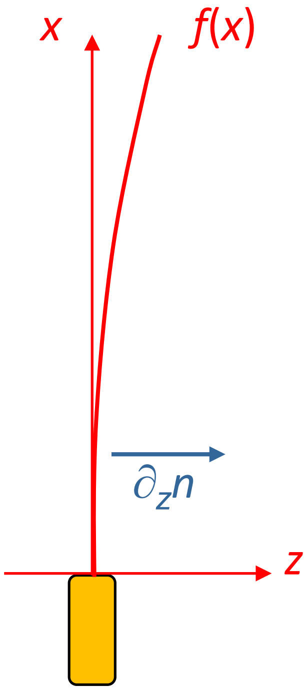
As a distance meter

- n expresses the speed of light in air
- With different n, a same distance is covered by different numbers (and fractions) of wave cycles
- What counts is not the n value at any point in space, rather the integral mean over the beam path:

  $l_0 = nl \rightarrow l_0 = \int_l n\mathrm{d}l \quad \longrightarrow \quad \int_l n\mathrm{d}l \rightarrow$
- The measured light *phase* is affected proportionally
  - If e.g. 10^{-6} uncertainty is sought, (at least) 10^{-6} must be achieved for n

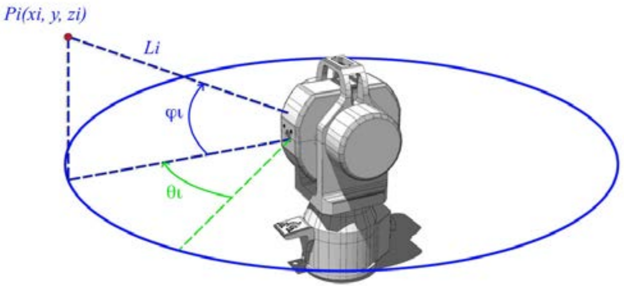
As a pointing device

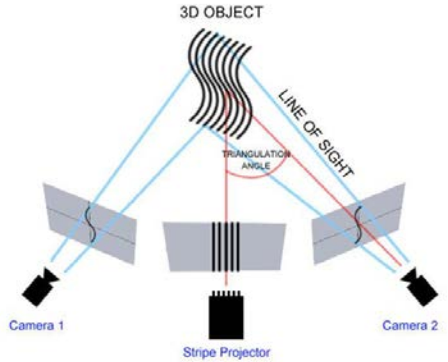
- The phase is not relevant
- The light "bends" due to the a refractivity gradient normal to the path
- The resulting path is parabolic: $f'(x)=\partial_z n/n$
- With a 1×10^{-6}/m gradient ($\sim$ 1 K/m), the bending is $f(15\text{ m}) \approx 0.1\text{ mm}$
  - With a reasonable knowledge of the gradient (e.g. 10% uncertainty), the effect of beam bending after correction can be kept below 10 µm

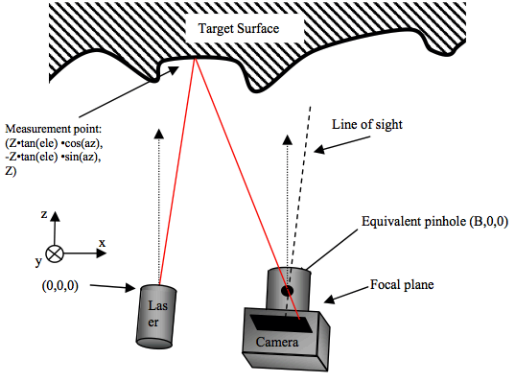


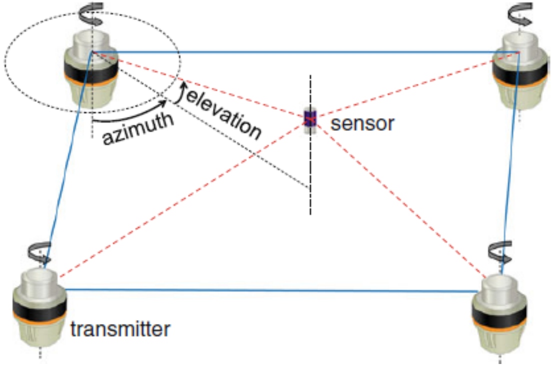
Existing pointing devices

- Spherical coordinates
  - Laser trackers
- Tri- (or multi) angulation:
  - Structured light
  - Laser scanners
  - iGPS
  - Photogrammetry
  - …







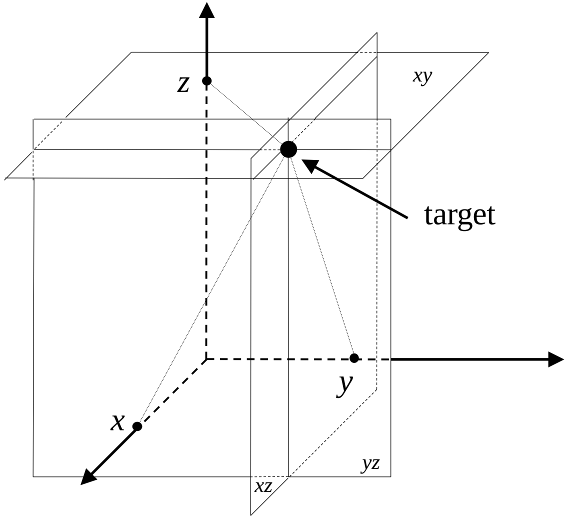


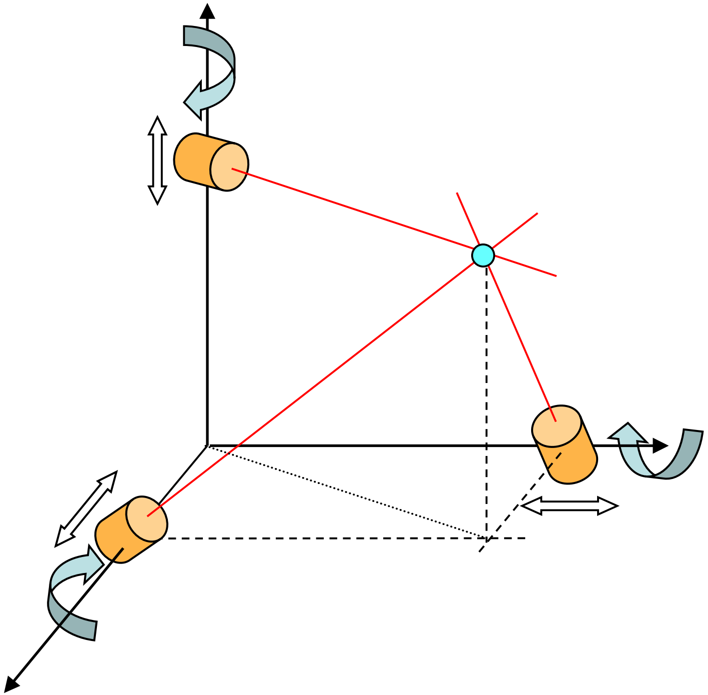
Pointing by angles: the only option?

- All these instruments
  - Point to a target by varying *angles*
  - These angles are *measured*; and possibly *controlled* (for tracking)
- Angles [dimensionless] alone cannot yield coordinates [lengths]; the essential link to a length is taken from
  - The interferometer/distance meter (laser trackers)
  - The mutual positions of the emitters/receivers (multiangulation, iGPS, …), usually precalibrated based on a calibrated artefact

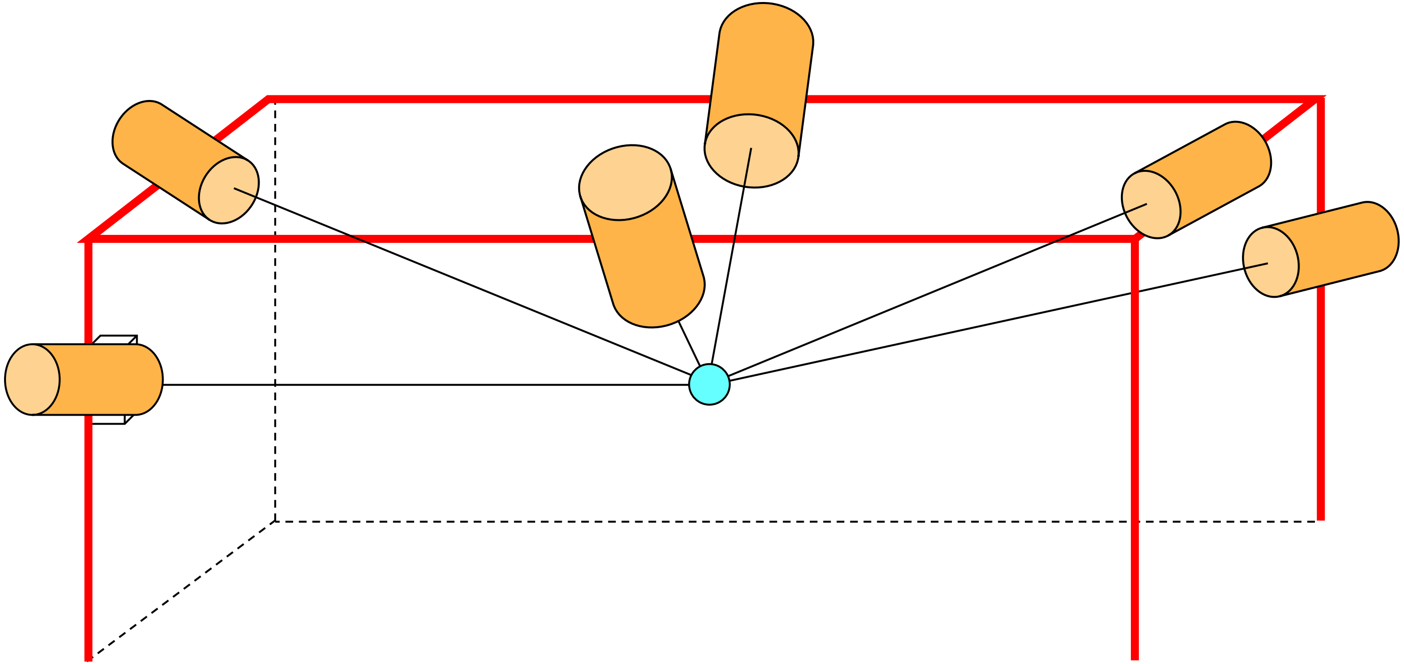
- InPlanT proposes a different option:
  - Pointing is achieved partially by angles and partially by a linear position
  - The angles are not measured, only the linear positions are

Concept of InPlanT
(*Intersecting Plane Technique*)





Possible redundancy

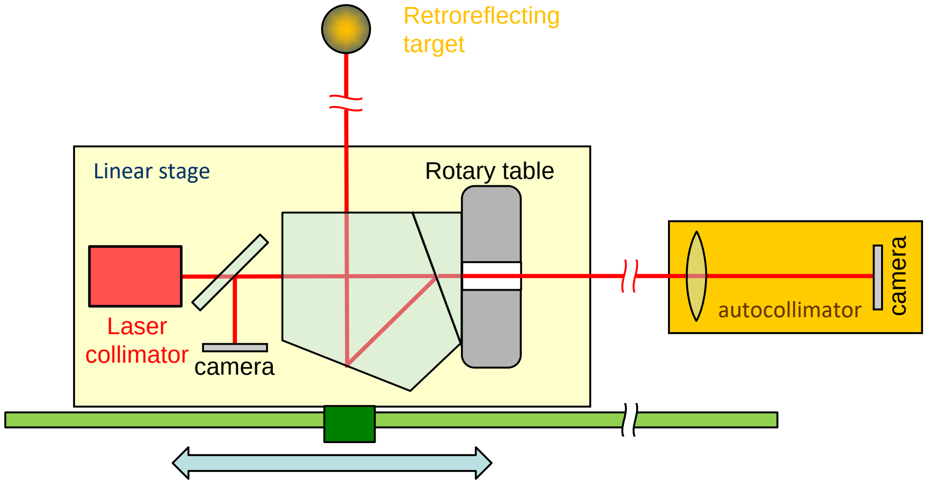


Main features of InPlanT

- Fully parallel measuring axes
  - Each measures a coordinated independently of the others (no kinematic seriality)
- Light used for pointing only; the actual measurements are
  - carried out by regular linear encoders
  - confined to the volume sides, where the environment may be not so harsh and possibly protected
- No interferometry
  - No need for measuring the refractive index of air
  - A moderate knowledge of its gradients suffices

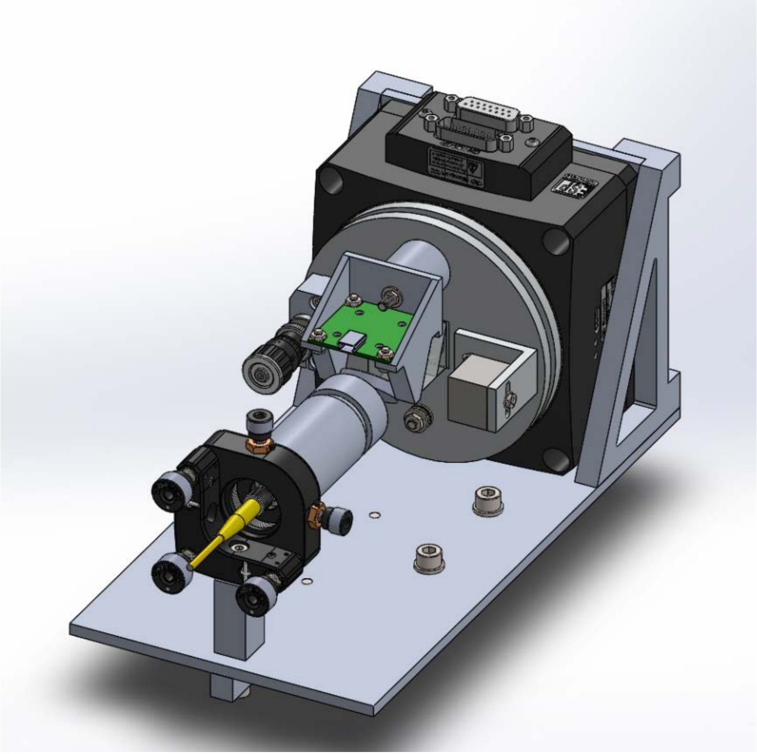
Design of each axis

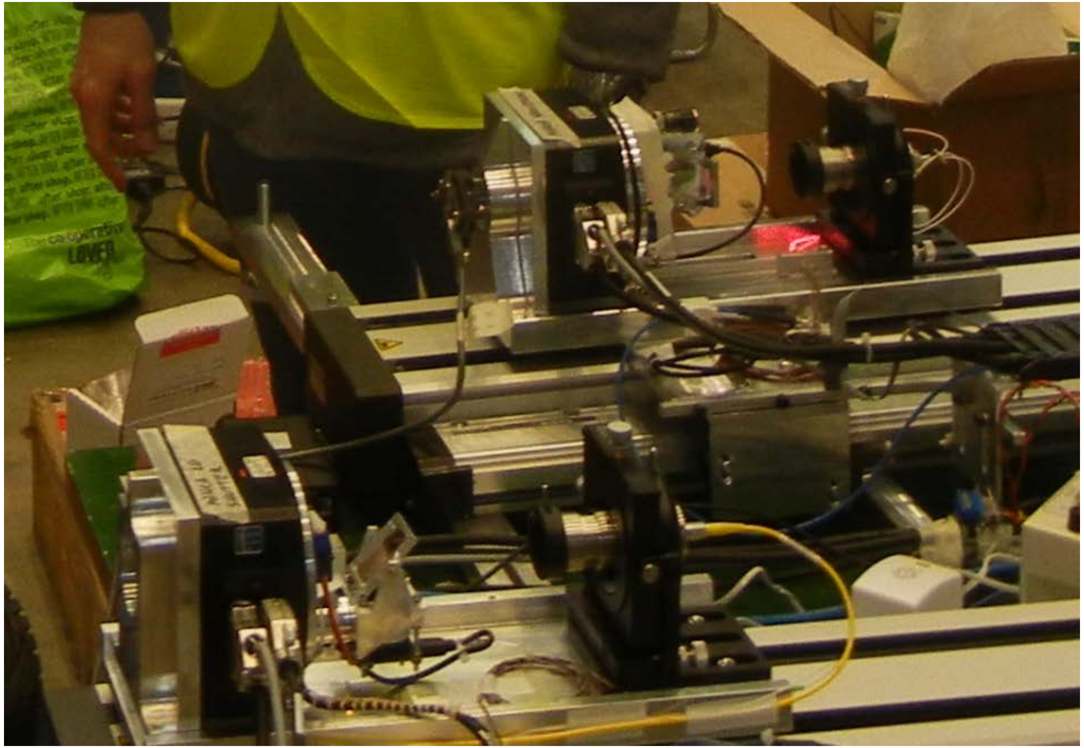
- A moving linear stage carries:
  - A rotary table (RT) with rotation axis aligned to the measurement axis
  - A laser collimator (fed by a fibre, not drawn) aligned to the rotation axis
  - A pentaprism attached to the RT which deflects the beam 90° regardless of its orientation
- The beam impinges onto a retroreflecting target
- The returning beam is deflected back by the pentaprism and impinges (through a beam splitter) onto a camera
  - The camera sees the (luminous) image of the retroreflecting sphere
- The position of the sphere in the camera image drives
  - Vertically, the rotary table
  - Horizontally, the linear stage
- When the image is centred (possible residuals are compensated), the linear position is measured by a linear encoder and constitutes the sought coordinate



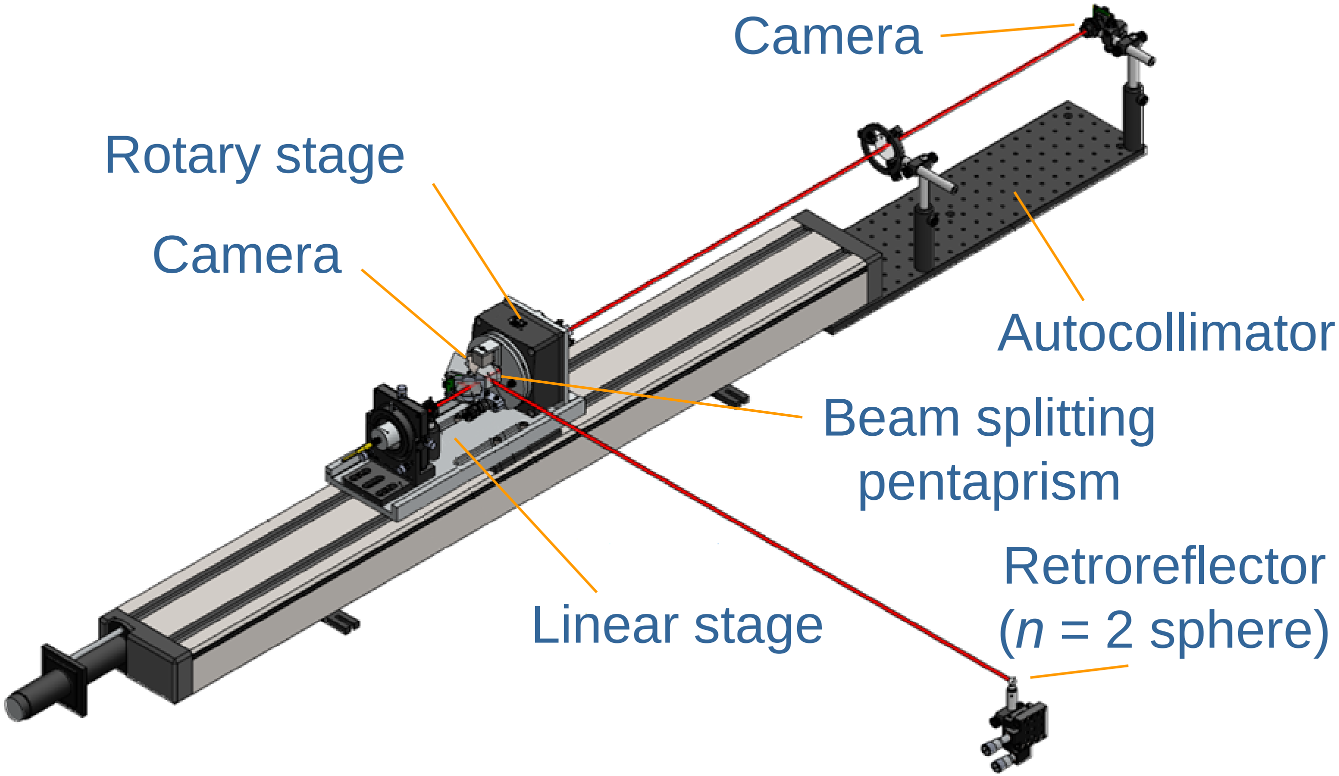
- The slider stroke is inevitably affected by yaw and pitch
  - To detect and correct, the pentaprism also separates the beam
  - The actual misalignment of the undeflected beam – and then the yaw and pitch – is measured by a still autocollimator at the end of the stroke

Design and realisation

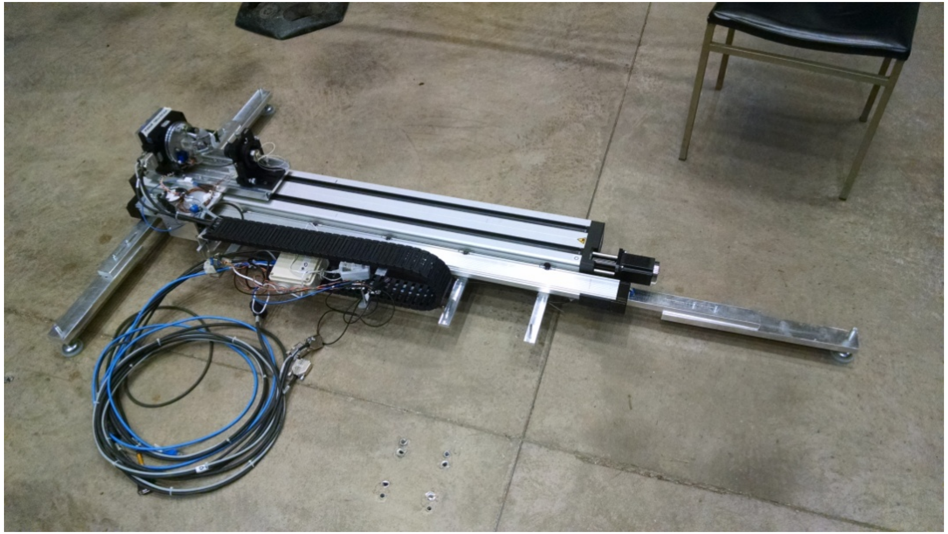




Overall design



Realised set ups



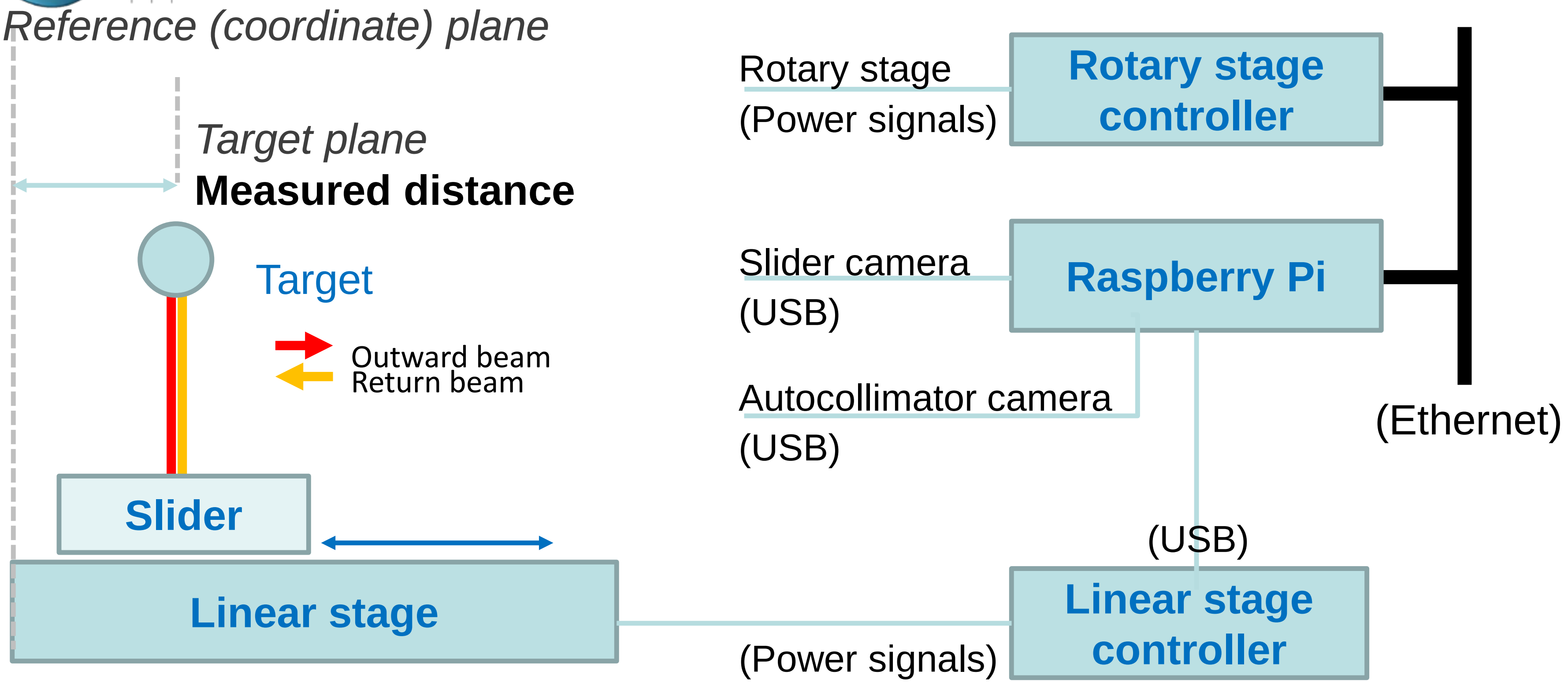
1 m stroke

2 m stroke

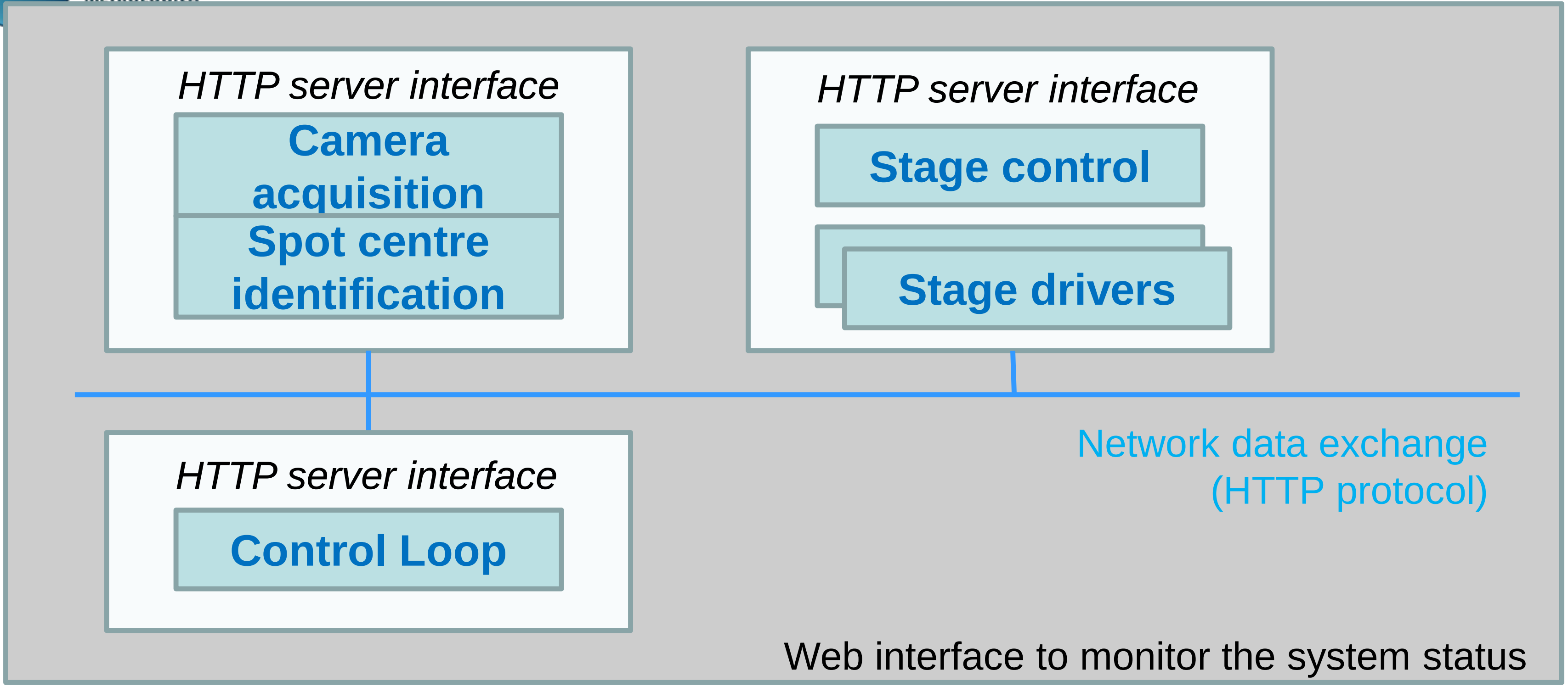
Limits of the prototype

- In principle, to achieve a $(10 \times 10 \times 5)\ m^3$ measuring volume, two 10 m and one 5 m axes are required
- Due to the budget limitation, the project prototype is limited to two axes only, with strokes of 1 m and 2 m, respectively
- Only the 2D coordinates of the projection of the target over a measuring plane can be measured at the moment, limited to an area of $(1 \times 2)\ m^2$
- However, measurements in a 3D space at full distance (e.g. at 10 m) are possible thanks to the mutual independence among axes

HW architecture

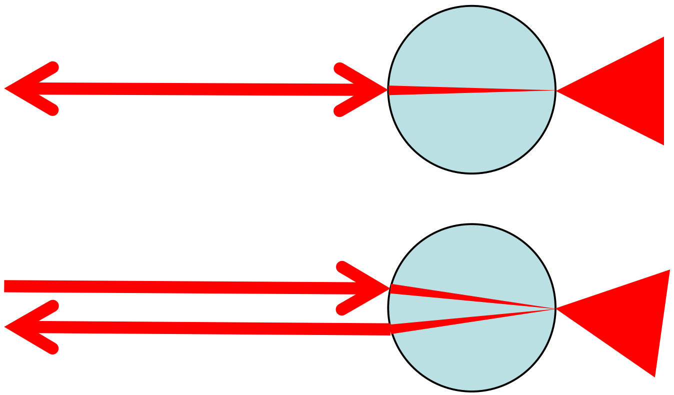


SW architecture – Raspberry PI



The retroreflecting sphere

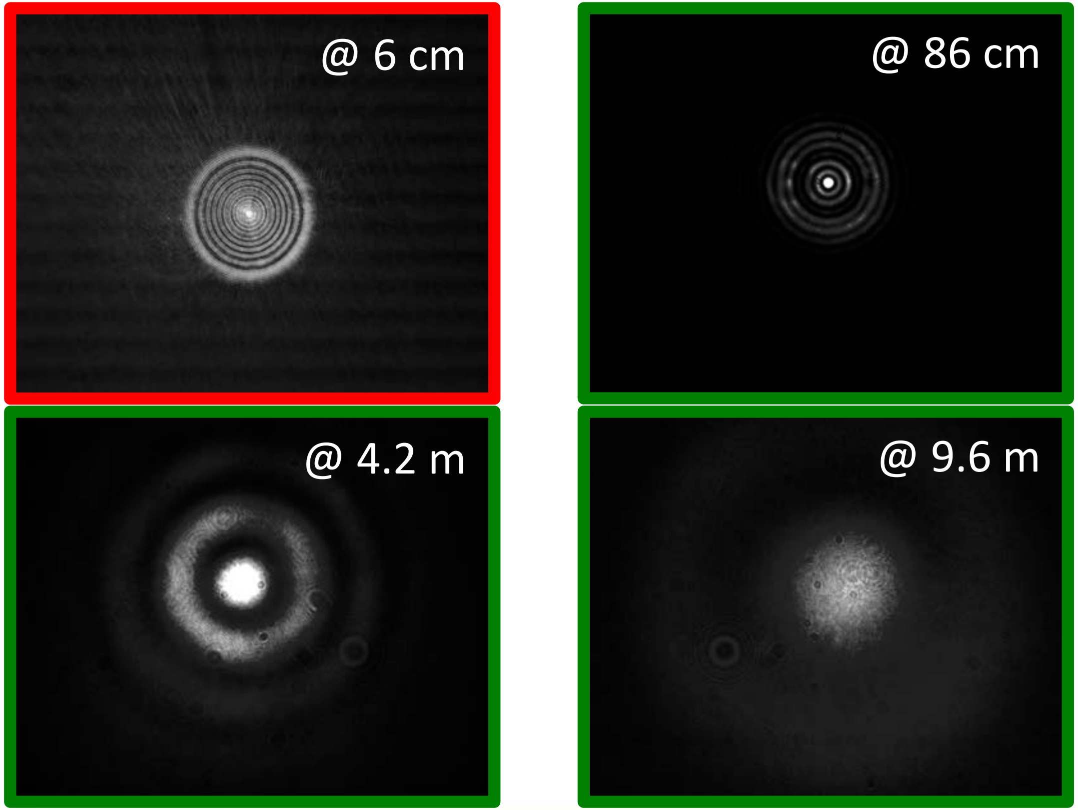
- The target is targeted from different aiming directions
  - Wide acceptance
  - Invariance of the localisation point with these directions
- The most isotropic geometrical element is the sphere
- When a sphere is made of S-LAH79 (glass with *n* = 2)
  - The retroreflected beam is parallel and collimated, very much as with a cube corner …
  - … within the limits of approximation of small angles



[Takatsuji et al., Meas. Sci. Technol. 10, 1999]

Images from the sphere

In lab, slightly different optical set up



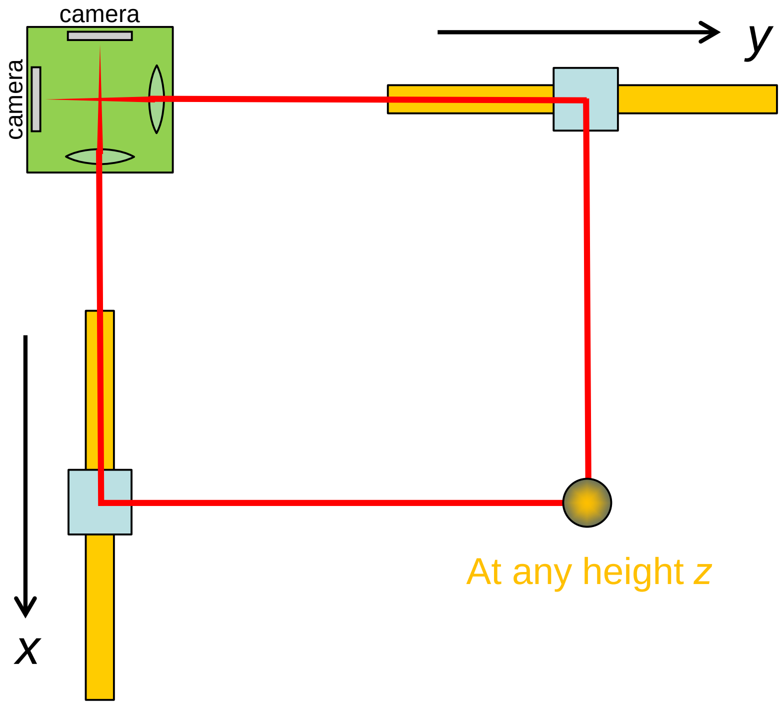
On field

The sphere images

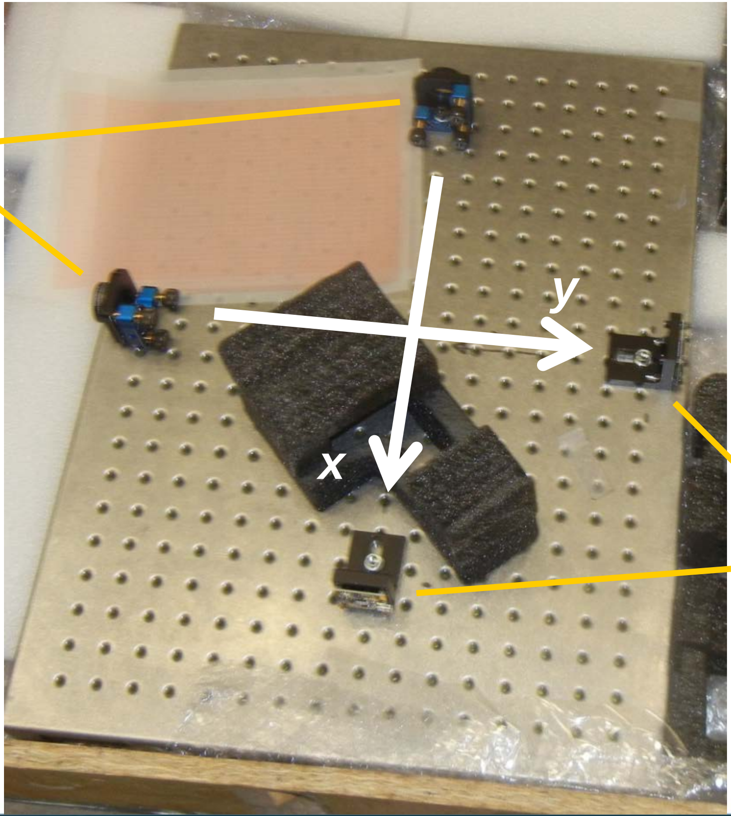
- It is a complex optical phenomenon, not fully understood
  - Some literature exists, but not for wide beams:
    [Yang et al. *Int. Workshop on Accelerator Alignment*, Grenoble (FR), 1999]
- The retroreflected light accumulates at certain angles
  - resulting in concentric rings
  - The longer the distance to the target the bigger the ring sizes, and the fewer visible rings
  - A challenge for the image algorithm to compute a point localising the pattern (not necessarily the centre)

The multiple autocollimator

- The multiple autocollimator measures yaws and pitches for compensation
- Effectively, it serves as the overall InPlanT reference frame
- The two autocollimators should be set orthogonal
  - To minimise the squareness error
  - Calibrated in laboratory



Autocollimator



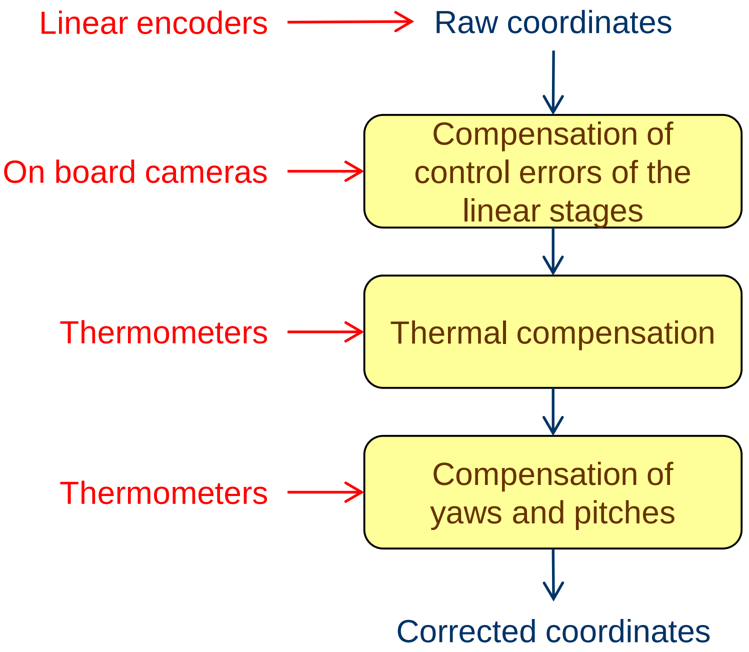
Sensitivity:
12 µrad/px

Experimental validation

- A bar with two spheres was attached to a high precision rotary table
  - Both the measuring plane and the rotation axis aligned to the vertical
- The generated positions laid on two circles
  - The rotary table assumed to be perfect
  - Any deviation from circularity attributed to the InPlanT device

Derivation of results

- Three compensations:
  1. Of the control error of the linear stages, by observing the displacements of the sphere images at the on-board cameras
  2. Thermal expansion of the linear encoders
  3. Yaws and pitches by observing the autocollimator signals

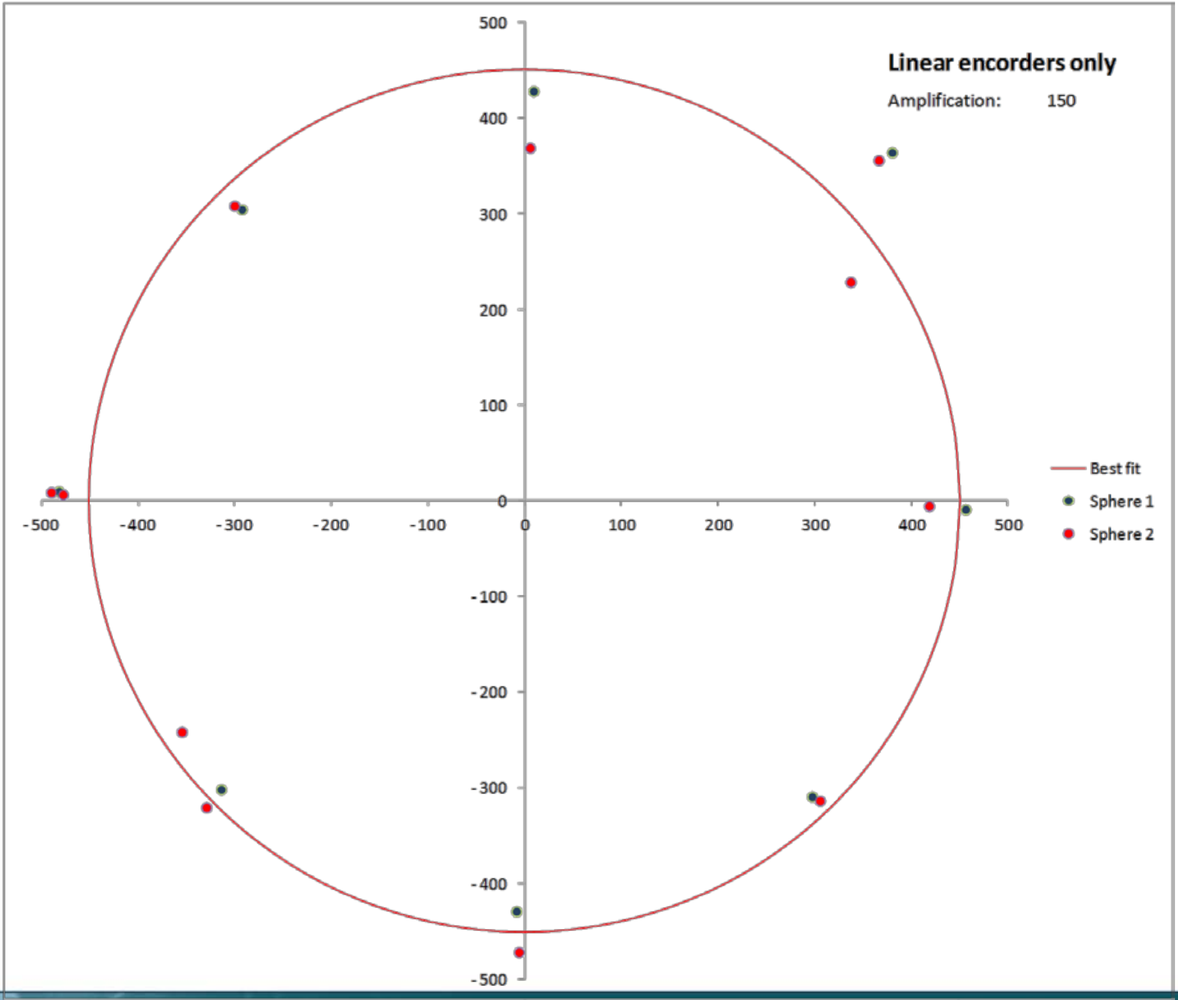


Testing conditions

Ball bar nominal length	500 mm
Rotation axis (*x*,*y*) coordinates	(450 mm, 450 mm)
No of angular positions	8+
No of points	19
No of outliers (discarded)	1
Temperature	(17.0 – 18.2) °C
Geometrical parameters to fit	(x_0, y_0, R_1, R_2) concentric fit

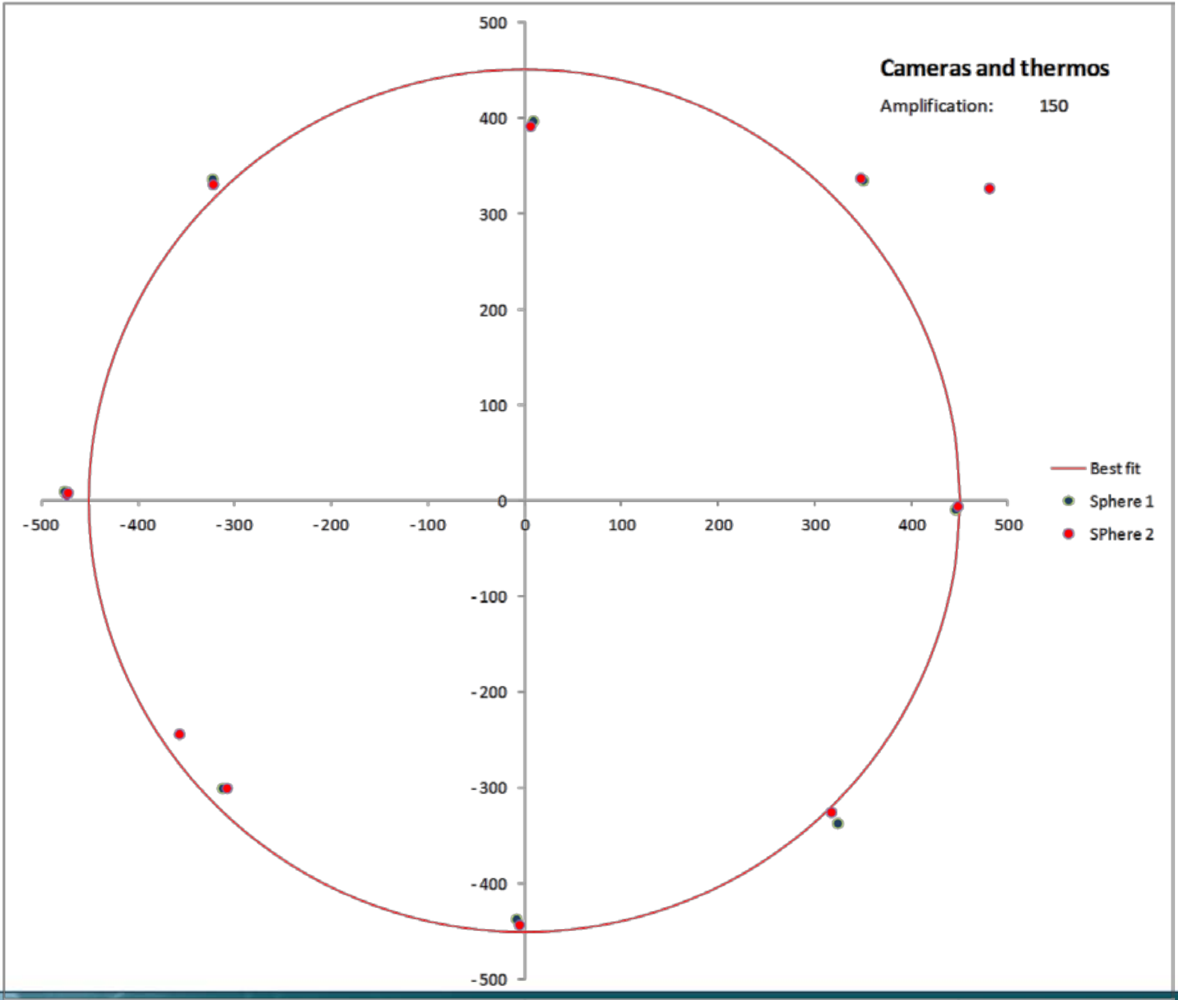
Results

Standard deviation of the fit:
276 µm



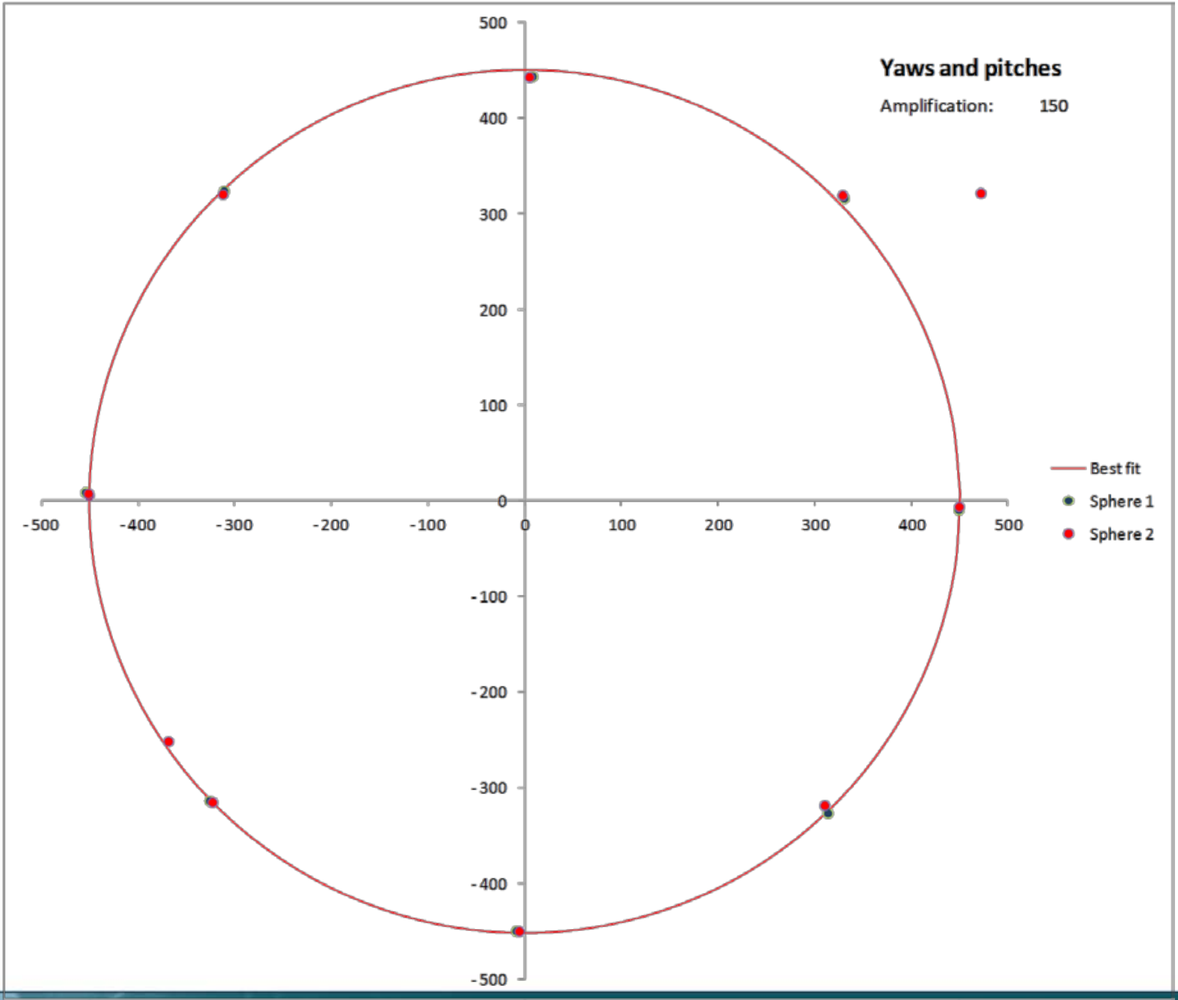
Results

Standard deviation of the fit: 196 µm



Results

Standard deviation of the fit:
45 µm



Conclusions

- An InPlanT working prototype was constructed
  - Limited to 2D and to a $(1 \times 2)\ \mathrm{m}^2$ area, but simulating 3D and $(10 \times 10 \times 5)\ \mathrm{m}^3$ in full
- The principle has been successfully validated
- An error standard deviation of 45 µm was achieved in the rotary table test in harsh conditions
- Further test data are currently being evaluated