

CARTESIAN APPROACH TO LARGE SCALE CO-ORDINATE MEASUREMENT: INPLANT

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Abstract

A novel paradigm of coordinate measurement is presented, named InPlanT. The target application is the industrial measurement of large workpieces in harsh conditions, e.g. in aerospace industry.

Like other techniques, a large measuring volume is covered by laser light with no contact. Unlike most other techniques, InPlanT relies on light only to point to a target, while the actual measurement is done by standard position sensors, such as linear encoders or interferometers. The actual coordinate measurement is relegated to the border of the measuring volume, possibly protected against a harsh environment.

The principle, and the characteristics and expected errors of the main InPlanT subsystems, are described. The preliminary experimental results of the most critical subsystem – responsible to detect the target – are promising.

Keywords: Large volume measurement, CMM, laser tracking

1. INTRODUCTION

Coordinate metrology is a key technique in dimensional metrology, largely used in manufacturing industry. Typical instruments – e.g. CMMs [1] – provide local metric volumes in which workpieces are measured. When workpieces are large – e.g. in aerospace industry – such volumes may not suffice.

A possible approach to overcome this problem is with portable coordinate measuring systems (CMS's), relocated flexibly to tailor form and dimensions of the workpiece. This way, only the workpiece portion in view of the CMS can be measured at once. Examples of such CMS's are laser trackers, laser tracers, theodolites and total stations, laser scanners, laser radars, photogrammetric equipment. Laser trackers and tracers are most accurate, being based on interferometry. Laser trackers are full CMS's in spherical coordinates, measuring the radial distance by interferometry and the polar and azimuth angles by rotary encoders [2]. Laser tracers are limited to the radial distance but enjoy an optimized interferometric set up enabling top accuracy [3]. A complete measurement may require multiple CMS relocations and data fusion techniques: either to bring full measurements into a same (workpiece) coordinate system, e.g. by stitching, or to combine information of individually incomplete measurements, e.g. by multilateration or multiangulation.

An alternative approach pursues the ideal scenario of making the whole environment – e.g. an hangar – metric, i.e. where the coordinates in a same coordinate system of any point in space throughout a (large) room are easily yielded. This fascinating approach was dreamed of as early as in the

late 60's. The first and most natural implementation was to adapt the GPS (*Global Positioning System*) principle to indoor applications, essentially by installing local pseudolites emitting the GPS signals indoor and by enhancing the sensitivity of the receivers [4]. However the achieved accuracy was not satisfactory for manufacturing applications. Ultrasound signals were also investigated, in conjunction with either IR triggers [5] or compasses [6]. A more successful implementation – referred to as *Indoor GPS*, *iGPS* [7] – has been based on multiangulation of fan shaped laser beams from a constellation of transmitters. A commercial product exists on the market which implements this approach.

All the above solutions are based on non Cartesian coordinate systems, typically used instead for small and medium size workpieces. Two key features make the Cartesian approach feasible: the *proximity* and the *serial measurement* (Fig. 1).

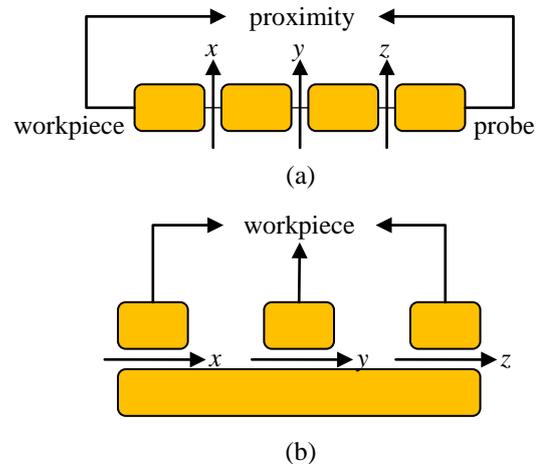


Fig. 1: Schematic diagrams of CMS: three axes separate four bodies (a) serially, or (b) in parallel.

A Cartesian CMM brings a probing system in contact with – or at least in the proximity of – the workpiece. This effectively closes the kinematic loop, either by contact or by short range optical sensing: the readings of the axes are then taken as coordinates of the probed point. The kinematic set up is serial, because the carriages carry each other in a sequence of orthogonal axes.

Representing vectors (points in space) in Cartesian coordinates – as opposed to e.g. spherical coordinates as for laser trackers – is appealing: the representation is most intuitive, the coordinates are dimensionally homogeneous, the linear combination of vectors results in the same linear combination of coordinates, and the sensitivity of the coordinates to the point – and vice versa – is globally

optimally conditioned with no singularity– e.g. the poles in spherical coordinates.

This paper introduces a novel approach to coordinate measurement intended for large volumes in harsh conditions, which is inherently Cartesian, not based on proximity, and measuring in parallel along the three axes. The current state of development is described, and the preliminary experimental results of a critical subsystem are presented.

2. INPLANT

2.1 Principle

InPlanT is an acronym for *Intersecting Plane Technique*. It is based on the simple idea that a point in space can be thought of as the intersection of three non parallel planes. In particular, if the planes are orthogonal to each other, their normal unit vectors form a Cartesian coordinate system, the planes are coordinate planes, and the position of each along its normal axis is the coordinate of the plane. The coordinates of the target are then the ordered collection of the positions (x,y,z) of the intersecting planes (Fig. 2).

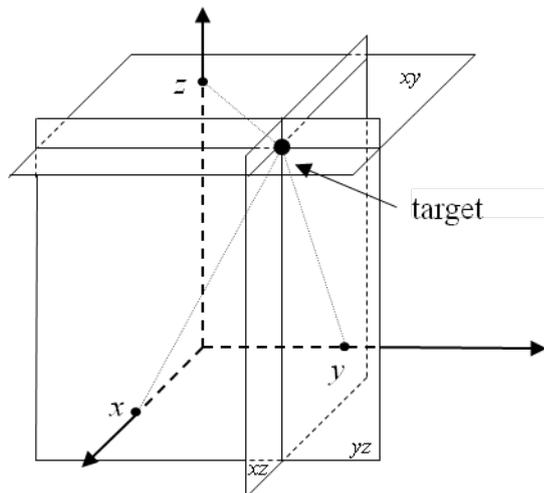


Fig. 2: The concept of InPlanT.

This approach is not based on proximity, as there is no such action as probing. Further, the actual coordinate measurements are relegated to the borders of the measurement volume, where the axes are. When the conditions of the measuring volume are harsh, the axes may still enjoy much more favourable conditions, either naturally or artificially by proper local protection.

InPlanT is *parallel*, as the axes work independently of each other, each yielding a single coordinate.

2.2 Objectives

The idea of InPlanT is being investigated in a European Research project jointly funded by the EMRP (European Metrological Research Programme) participating countries within Euramet and the European Union, named LUMINAR (Large-volume Unified Metrology for Industry, Novel Applications and Research) [8]. InPlanT is part of the Work Package 1 – *Innovative measuring systems* – whose overall objective is to achieve an accuracy of $50\ \mu\text{m}$ over a volume of $(10 \times 10 \times 5)\ \text{m}^3$ in harsh conditions, e.g. in a hangar.

2.3 Plan of work

To prove the concept of InPlanT, four main steps are foreseen. As InPlanT is a parallel measurement, the first two steps focus on a single axis.

1. Generating a coordinate plane and detecting a target;
2. tracking the plane onto a target and measuring its position – effectively a coordinate of the target;
3. duplicating the axis and combining the coordinates together;
4. validating experimentally in harsh conditions.

Being a proof of concept, steps 3. and 4. are limited in scope, resorting to simulated conditions as much as possible to save costs: two axes only are foreseen, with limited strokes (1 m and 2 m, respectively), in artificially harsh conditions. The simulation consists in posing the target far off the axes as if it were in a full $(10 \times 10 \times 5)\ \text{m}^3$ volume (14.1 m plane diagonal, worst case), and with significant component in the direction of the missing axis.

Currently, we have completed step 1., and are starting the successive ones. In the following subsections, the four steps are described. The next section illustrates results and achievements of step 1.

2.4 Generating a coordinate plane and detecting the target

The measurement should be without contact, from a distance. The coordinate plane in question is made of light, and the target is a retroreflector which returns the light when illuminated. More specifically, the plane is made of a collimated laser beam, and the retroreflector is a $n=2$ sphere. This latter choice is motivated by the wide angular acceptance required to the retroreflector – wider than an octant – which makes a usual corner cube unfit.

Several set ups were considered to turn a laser source into a plane of light (Fig. 3):

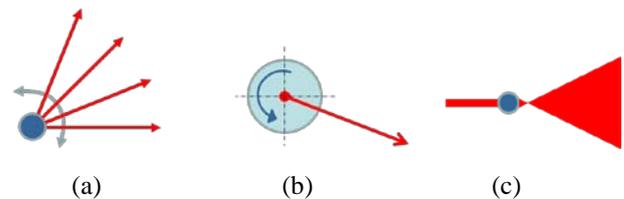


Fig. 3: Alternative set ups to generate a plane of light: (a) tracking the target; (b) continuous rotation; (c) persistent light fan.

- (a) Tracking the target. The plane is a conceptual locus, but effectively it only serves in the direction to the target. A standard laser source is mounted onto a servoed rotary table, the angle being locked to the beam returning from the target. This set up suffers minimal power waste as (almost) the full optical power constantly impinges onto the retroreflector. On the other hand, it requires a sophisticated and expensive rotary table and servo.
- (b) Continuous rotation. Where the target is in the coordinate plane is irrelevant to the InPlanT principle. A laser source is rotated continuously independently of the angular position of the target in the plane.

When the beam impinges onto the retroreflector, a peaked returning light is detected. This set up is simple and inexpensive, but results in a major loss of power, the farther the target the worse the loss. Also, the usable signal is available only once a route: to get sufficient sampling rate, the rotary stage – a spindle effectively – must be high speed. This set up was preferred: see next section for more details.

- (c) Persistent light fan. A cylindrical beam – i.e. with a circular cross section – is shaped into a persistent plane by means of suitable optic components (e.g. an orthogonal cylindrical lens, or a coaxial conical mirror with 90° apex angle). Similarly to set up (b), it is inexpensive but with major power loss: it is static with no requirement for motors, and the returned signal is continuous but very weak. Depending on the optic components used, the fan angle may not cover the measuring volume in full.

Set ups (a) and (b) may be blended into a hybrid one: a rotary table oscillates about the angular position of the target. The tracking would be much less stringent than in (a), as the angular tolerance about the central direction to the target would be now the oscillation angle instead of the much smaller view angle. Much less power would be lost than in (a), as the emitted power would be distributed under a much smaller angle. On the other hand, the table would be required high angular acceleration to provide sufficient sampling rate.

The plane of light may not be perfectly planar in fact. Let us call “*coordinate surface*” the actual locus of the positions in space illuminated by the laser. As it effectively links the target to the axis, any planarity error results in as much error in the measured coordinate. There are two main sources of planarity deviation:

1. The light leaves the emitter in directions not always orthogonal to the axis. This is fully controlled by the optical and geometrical quality of the emitter. A constant squareness error across all angular positions about the axis would result in a conical coordinate surface (*conicity error*); a variable squareness error in a “orange squeezer”-like coordinate surface; an angular dependent longitudinal shift in a sort of spiral stair with periodic pitch (null over a full route). These errors are expected to be very repeatable: prior characterisation would allow software compensation.
2. The light bends after leaving the source, due to air refractivity – more precisely to the component of its gradient orthogonal to the light propagation [9]. This problem is common to all instruments relying on straightness of light rays, e.g. laser trackers and photogrammetric equipment. In InPlanT, the bending occurring in the coordinate surface gives rise to no coordinate error: only the projection of the gradient onto the coordinate axis results in an error. The most critical axis is z , as the gradient is usually close to vertical. In a typical situation of a 1 K/m vertical thermal gradient, this error would amount to 50 μm at maximum (horizontal) distance of 10 m: a coarse measurement of the gradient would mitigate the problem to satisfactory accuracy.

The detection of the target is based on the distance of the ongoing to the retro-reflected coordinate surface, sensed by suitable photodetectors. This is similar to what other tracking devices – such as laser trackers and tracers – do. In InPlanT though the detection is interesting in the coordinate axis direction only, as the angular position in the coordinate surface is not relevant. The detection signal is continuous and signed, suitable to feed the tracking of the coordinate surface onto the target (see below).

2.5 Tracking the coordinate surface onto the target and measuring its position

The emitter generating the coordinate surface is mounted on a servoed linear stage. A control system is fed with the target detection signal as in § 2.4, and locks the stage accordingly. As a result, the coordinate surface is kept constantly through the target. The position of the stage – as measured with a position sensor such as a linear encoder or an interferometer – is then the sought coordinate along the axis.

The main error sources are expected to be the following:

1. Misalignment of the emitter, resulting in a coordinate surface not orthogonal to the axis. This is equivalent to a squareness error of the axis to the other two.
2. Pitch and yaw of the stage. They are most relevant, as the several metre optical Abbe arm amplifies the errors. To mitigate this, software compensation can be applied, based either on predetermined kinematic functions if they are stable over time – similarly to CMMs – or on on-line angular measurements by means of suitable sensors.
3. The other kinematic errors are not expected to contribute errors. The scale is of sufficient accuracy, and the Abbe arm of the emitter to the scale can be kept to acceptable values by design. Therefore, the scale error can be kept negligible. The InPlanT principle is insensitive to all other kinematic errors (roll and straightnesses).

2.6 Combining coordinates together

Each axis yields a coordinate independently of the others. A set of three yielded by mutually orthogonal axes constitutes the Cartesian coordinates.

The main error sources are expected to be the following:

1. Squareness. This is identical to the case of CMMs. This error can be reduced either by careful adjustment or by software compensation, or by both. Standard techniques can be applied, such as the repeated measurement of a same standard of size sequentially aligned along different coordinate plane diagonals. This error is not distinguishable from a squareness error of the coordinate surfaces to the axes.
2. Dead weight deformation. The axes are metre long, and may suffer significant bending due to dead weight. The amount and distribution greatly depends on the number, distribution and nature of the supports on which the stage guides rest. A preadjustment of individual axes may require refinement in-situ. Also,

the vertical axis might have been preadjusted horizontally in lab, resulting in different bending.

Due to the interdependence of the geometrical errors of individual axes and of the whole system, the compensation in step. 2 and 3. might be carried out – or refined – simultaneously at step 3..

2.7 Experimental validation

This step is the farthest ahead in the project. The experimental plan will be defined to best tailor the findings on individual subsystems as developed in steps 1-3.

3. DETECTION OF THE OFF-PLANE TARGET POSITION – EXPERIMENTAL RESULTS

The purpose of this subsystem is to generate a nominally planar coordinate surface as described in § 2.4 (b) and to detect the position of the target off the surface. Thanks to the optical properties of the $n = 2$ spherical target, the reflected beam is collimated, parallel to the incident beam, and offset twice the distance d of the beam to the sphere centre¹. The detection is then based on the distance of the reflected to the incident beams. The resulting signal is used as error signal to lock the coordinate surface onto the target, as described in § 2.5.

Figure 4 sketches the experimental set up. Its main components are described in the following paragraphs.

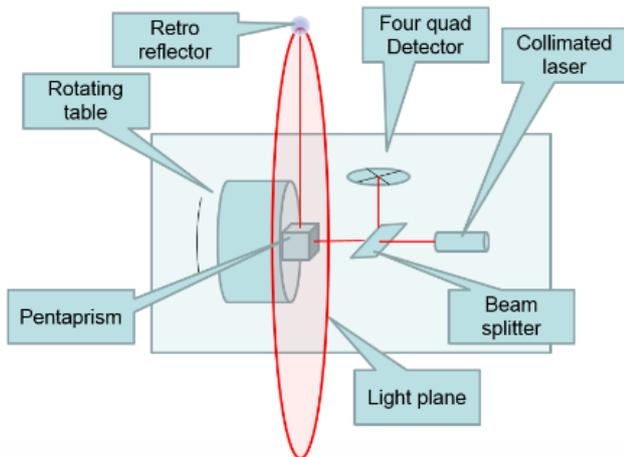


Fig. 4: Schematic of the plane generator and detector assembly.

3.1 Light plane generator

The laser source is a fibre-coupled laser diode emitting 20 mW optical power at 630 nm. The laser beam is folded 90° by a pentaprism². The pentaprism is attached to a high

¹ This is true when the spherical aberration is negligible, i.e. when the section and the distance to the centre of the impinging beam are negligible to the sphere diameter.

² Pentaprisms enjoy the optical property of folding a light ray in the prism plane of symmetry, of a nominally 90° angle independent of the pentaprism angular position in that plane. Effectively, they serve as nearly perfect 90° folders.

speed spindle to generate a rotating laser beam laying on a (nominal) plane orthogonal to the incident laser beam. In this preliminary proof of concept, the motor of a hard disk unit was used. Its mechanical quality allowed micrometric rotation at the speed of 120 revolutions per second (Fig. 5).



Fig. 5: A detail of the pentaprism mounted on the hard disk motor. The pentaprism and its triangular support (vertex angle 22.5°) were carefully adjusted to make their centres of mass lay onto the axis of rotation, to achieve good balance.

3.2 Target

The retroreflector is a glass sphere with refractive index $n \approx 2$. The glass is LAH-79, manufactured by Ohara (Japan), and the sphere has got 10 mm diameter and $\lambda/4$ form error. The ideal behaviour with no spherical aberrations would be that of a perfect retroreflector: the reflected beam would be collimated, parallel to the incident beam, and offset twice the distance d to the centre. The real behaviour is far from ideal, with significant aberrations. In spite of this, the reflected and incident beams are coaxial when they are centred onto the target, otherwise the optical centre of mass of the reflected beam is offset. Independently of the behaviour of the reflector, a detector able of measuring this offset is the heart of the device.

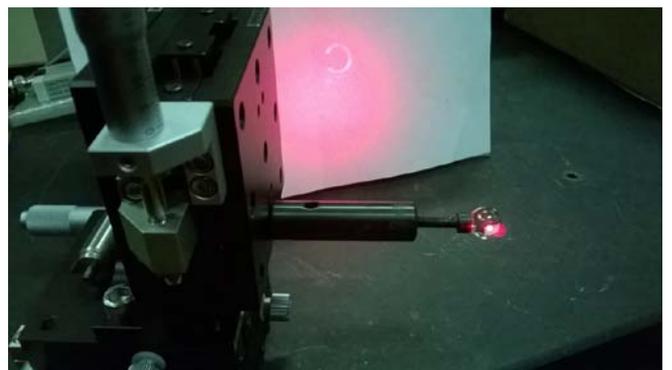


Fig. 6: The target sphere mounted on a vertical translator used to calibrate the detector.

3.3 Detector

The detector is based on a four quadrant photo-diode sensing the beam reflected back from the target and spilled by a beam-splitter. Each quadrant is connected to a transimpedance circuit generating a voltage signal proportional to the impinging light. The four signals are

summed and subtracted in pairs to yield the x and y positions. They are normalised to the sum of all quadrants, s , to immunise against the intensity (Fig. 7).

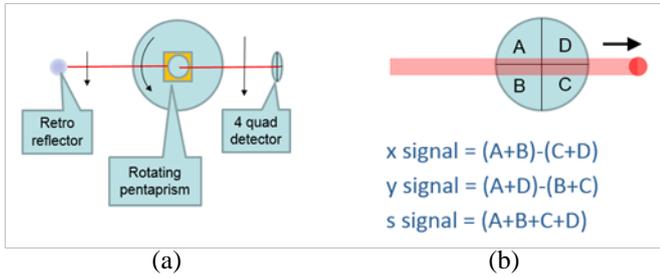


Fig. 7: Schematic of the laser beam trajectory when the target is perfectly on the coordinate surface: (a) at the target; (b) at the detector.

When the laser beam encounters the target along its rotation, the reflected beam counter-rotates and crosses the four quadrant detector. Figure 8 shows the resulting signals. The central portion shows the case of the target laying on the coordinate surface: the total intensity s (pink) is null until the spot enters the detector, then increases and reaches a maximum, and finally decreases to zero when the spot leaves. The x signal (blue) changes sign when the spot crosses the centre. The y signal (yellow) is substantially null, the quadrants being always balanced. As soon as the target moves off (Fig. 8, top and bottom), the y signal gets unbalanced – either positive or negative – proportionally: this is taken as the sought error signal.

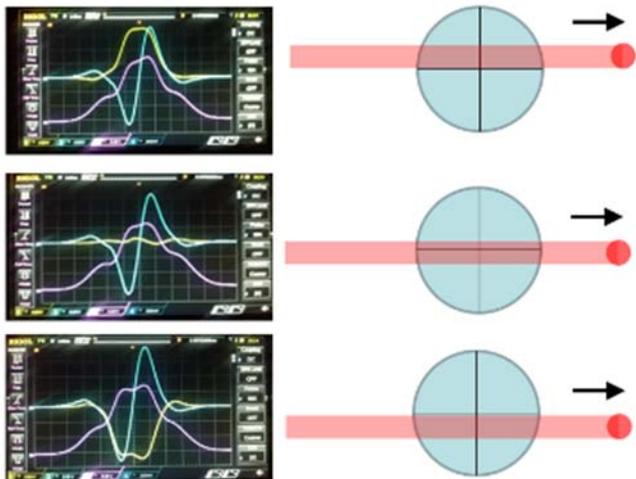


Fig. 8: x (blue), y (yellow) and s (pink) signals in the time domain. The target is above (top), laying in (centre) and below (bottom) the coordinate surface.

3.4 Acquisition electronics and software

The three voltage signals x, y, s were converted by an ADC with parallel conversion at 2.5 Msample/s at 14 bit, and input to a PC. The x and y signals were first normalised to s to eliminate the undesiredly variable intensity of the returning light. The signal of interest (y in our example) was numerically integrated over the full signal span (few microseconds), resulting in a value proportional to the offset

of the coordinate surface to the target. As this was generated and made available at each beam revolution, the error signal was updated at 120 Hz, i.e. every 8.3 ms.

Because the beam splitter spilling the returning beam and the photodiode were both non rotating, the light spot swept the detector along directions dependent on the angular position of the target in the coordinate surface. When the target was angularly opposed to the detector (counter-phase), the sweeping direction was aligned to a photodiode axis (as in Fig. 7 and 8); when it was in quadrature, the sweeping direction was aligned to the other axis, thus reversing the role of the x and y signals; in between, the direction was oblique, and the x and y signals combined. As the angular position of the target was unknown, any sweeping direction could be met. A software routine was developed able to unbundle the x and y signals real time, and to yield the sought error signal for any angular position of the target.

3.4 Preliminary results

The response curve of the detector was investigated by offsetting the target off the coordinate surface by means of a precision micrometer screw, while recording the detector output. Measurements were repeated at different angular positions and distances of the target. The resulting curves exhibited linear central portions and symmetrical non linear side portions at large offsets. The linearity spans were few tens of a millimeter with the available 10 mm diameter sphere.

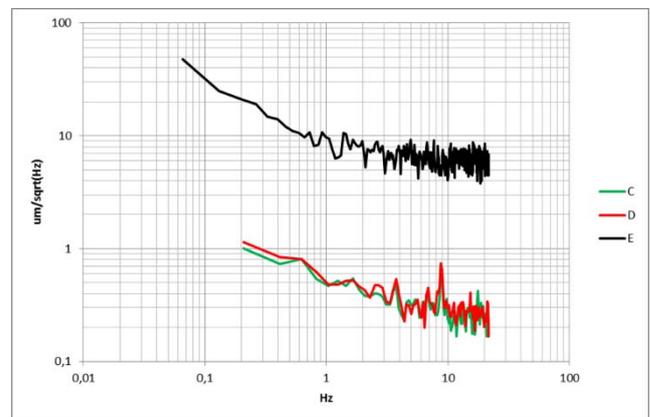


Fig. 8: Noise spectral density [$\mu\text{m}/\sqrt{\text{Hz}}$] of the detector signal at different target distances: 0.5 m (green and red, different angular positions) and 7 m (black).

The detector signal is to be used to feed a locking circuit. Therefore, the most important characteristic of the signal is its ability of detecting small offsets about zero. The investigation of this characteristic was carried out resorting to the noise spectral density of the detector signal: it was recorded while the target was kept still close to balance, and converted to micrometres via the response curve. Figure 9 shows the noise spectral density obtained in three working conditions. At high frequencies, the curves asymptotically converge to the white noise due to opto-electronics circuitry. At low frequencies, the noise increases due to air turbulence

and to the thermo-mechanic variation of distance to the target – mostly thermal expansion of the supports.

The noise increased with the distance to target, due to the reduced optical power. The noise limit was found at about $1.5 \mu\text{m}/\sqrt{\text{Hz}}$ and $7 \mu\text{m}/\sqrt{\text{Hz}}$, at 0.5 m and 7 m distance, respectively.

4. CONCLUSIONS

InPlanT is a novel paradigm of coordinate measurement, addressing the problem of large workpieces in harsh conditions, e.g. in aerospace industry.

The principle and the overall system architecture is fully worked out. The current state of implementation is focussed on the first and most critical subsystem, responsible for detecting a target without contact. A laboratory prototype has been developed and tested. The results prove the principle and are promising for the continuation of the project.

ACKNOWLEDGEMENTS

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