Roll angle in 6DOF tracking

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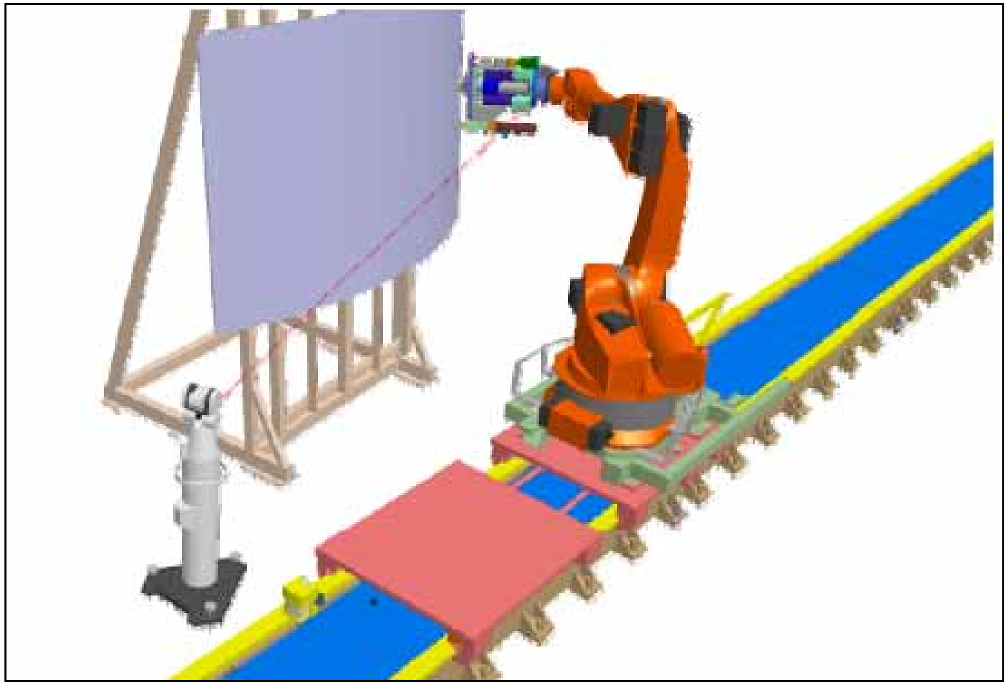
Author: **Stephen Kyle**
Senior honorary research fellow, University College London
Honorary research fellow, Coventry University
Stephen.Kyle@micronSpace.com

Presenter: **Steven D. Hand**
Director of Fabrication-Nuclear
Chicago Bridge & Iron Company
shand@cbi.com

The problem area – 6DOF tracking

micronSpace
Stephen.Kyle@micronSpace.com
s.kyle@ucl.ac.uk



Manual – Leica T-Probe

Robot – Leica T-Mac

Examples above from Leica Geosystems (Hexagon) show 6DOF probes in use:

- Tracked point is not feature point
- Need offset length PLUS …
- Angular orientation - roll, pitch and yaw

micronSpace
Stephen.Kyle@micronSpace.com
s.kyle@ucl.ac.uk

Laser tracker 6DOF probes

Leica Geosystems

Automated Precision (API)

Combined roll, pitch and yaw calculation

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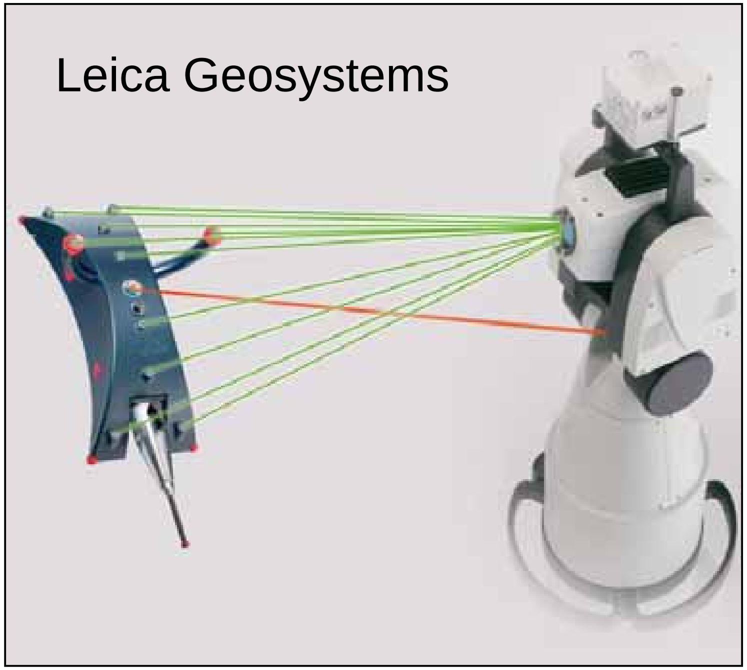
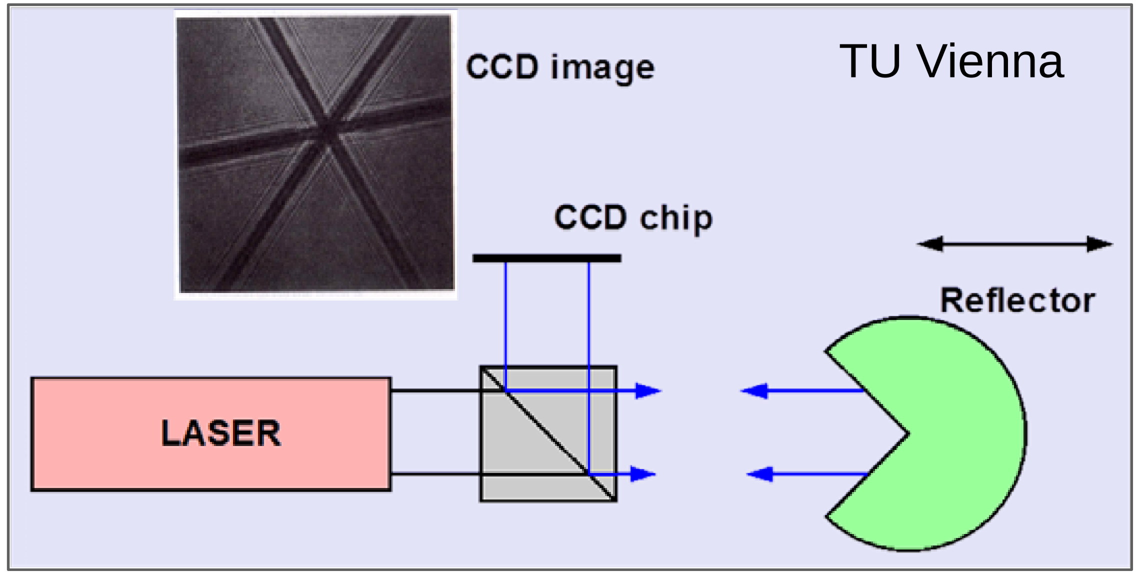
Stephen.Kyle@micronSpace.com
s.kyle@ucl.ac.uk





Leica Geosystems

- Targets surround reflector
- Separate zoom camera images targets (green lines in image)
- Orientation angles from standard space resection

Technical University of Vienna (archive)

- Return interferometer beam also generates shadow of reflector edges (a 3D shape)
- Orientation angles derived from shadow image of edges (parallel projection)

Alternatively calculate (pitch + yaw) and roll

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Stephen.Kyle@micronSpace.com
s.kyle@ucl.ac.uk

- Example: camera on probe sights back to tracker head target
  - Normal angle lens, e.g. 50˚
    (this example is similar to acceptance angle of reflector)
  - 2K x 2K imaging chip
  - 1/20 pixel interpolation
- Potential pointing accuracy 50˚ / (2000 x 20) = 5 arc sec (approx.)
  - Equivalent to 25µm at 1m offset which is a good accuracy level for probing systems designed with ever increasing offsets
- BUT .. roll angle still required
  - Further discussion on following slides

Roll angle from space triangle

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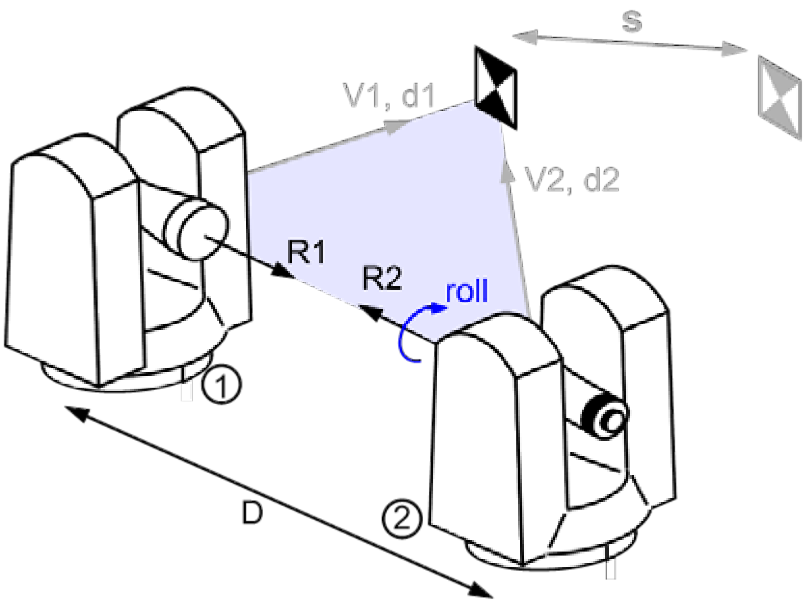
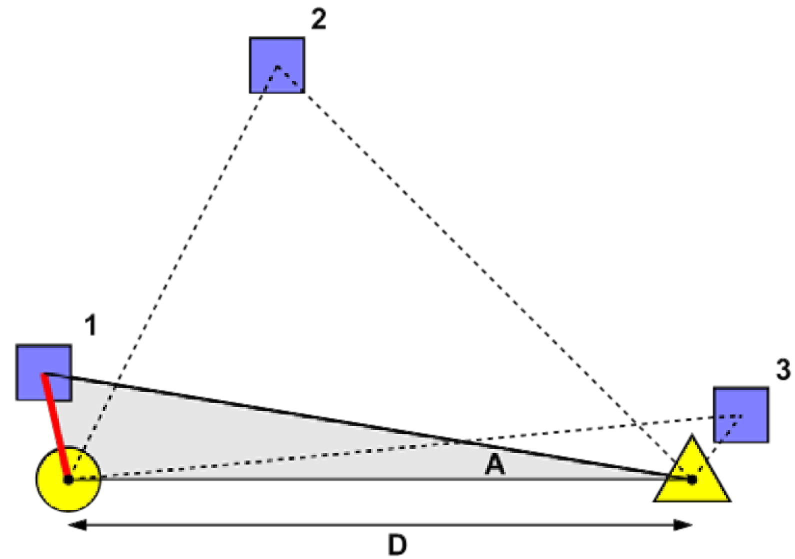
Stephen.Kyle@micronSpace.com
s.kyle@ucl.ac.uk





Non-levelled theodolite orientation

- Make reciprocal pointings R1, R2
- At assumed scale, (2) is then fixed relative to (1) except for roll angle
- Make pointings V1,V2 to any offset target. Intersection of V2 with V1 fixes roll angle
- True scale then from scale bar s, direct separation D or ranges d1,d2

Generalized space triangle

- 3 possible offset target positions shown in blue
- 2 angle measuring devices shown in yellow
- If one device moving (tracked by other), it is convenient using targets close to baseline
- Also convenient is use of a target attached to a device, e.g. as at (1) shown in red
- Attached target vector then found by calibration, not direct measurement

Roll accuracy in space triangle

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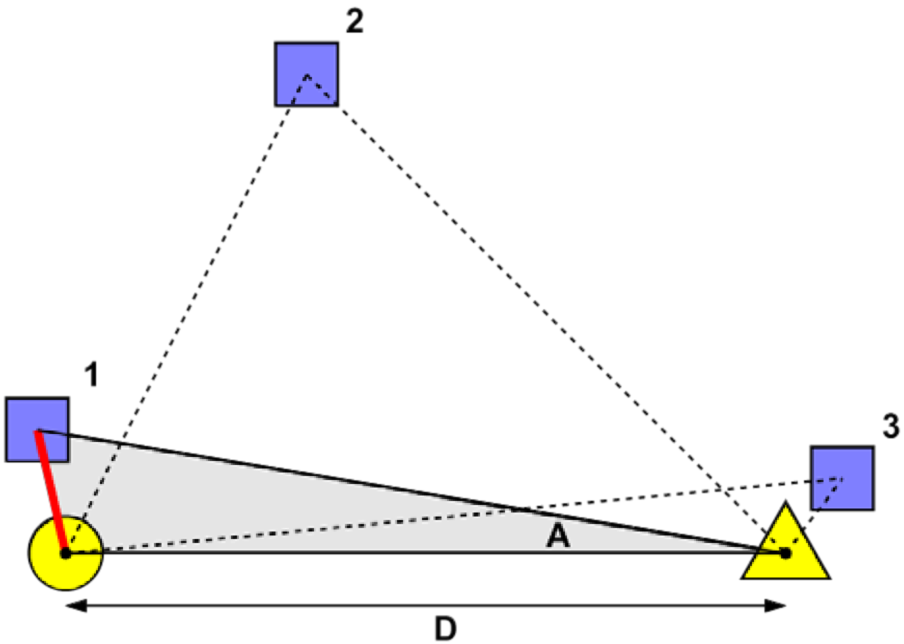
Stephen.Kyle@micronSpace.com
s.kyle@ucl.ac.uk



For a given pointing accuracy

- Roll less accurate when targets closer to baseline (example locations 1,3)
- Roll cannot be calculated when target is on baseline
    - Roll plane disappears in this case

Two conditions identified for optimal roll

- Lo-res, hi-offset
  For devices of moderate angle resolution (lo-res), keep target well off baseline (hi-offset), with angle A ideally close to 90 °
- Hi-res, lo-offset
  For devices with high angle resolution (hi-res) a small offset angle A is sufficient (lo-offset). This is a good strategy, if it can be implemented, for a laser tracker.

Reciprocal theodolite pointing: an aside

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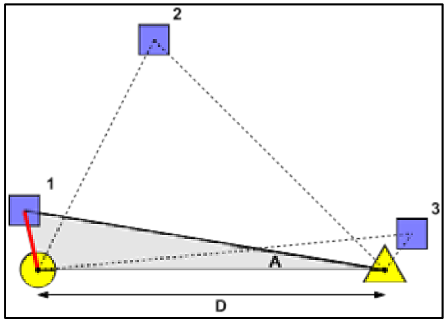
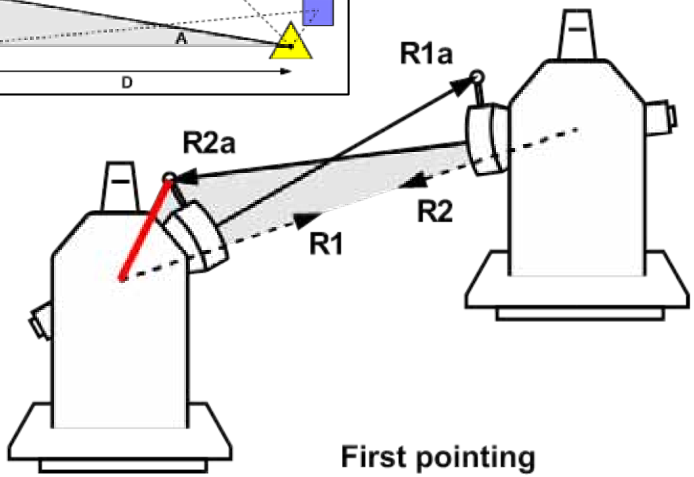
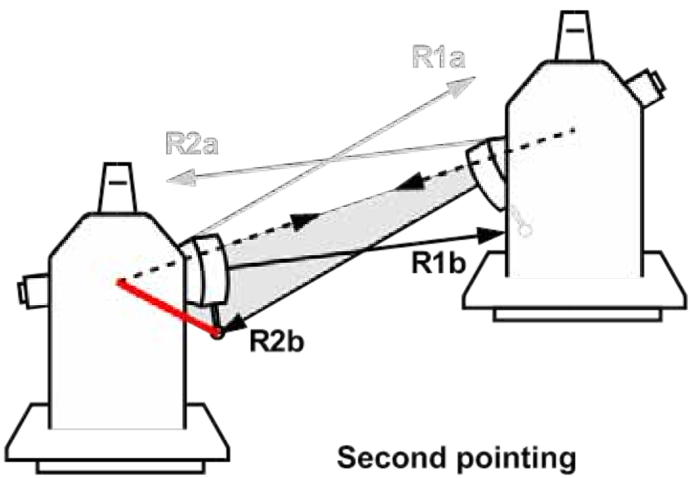
Stephen.Kyle@micronSpace.com
s.kyle@ucl.ac.uk





First pointing



Second pointing

To obtain pointings between instruments

- Attach offset targets to telescopes
- Make first pointing in face left (standard telescope position)
- Make second pointing in face right (inverted telescope position)
- Mean vector of each pointing pair gives the direct centre-to-centre vector

- Note how roll can then also be derived from the same pointing data.
- 4 possible roll planes (2 shown shaded)
- Compare roll plane shown in first pointing with inset of generalized space triangle

- Not normally used; this is lo-res, hi-offset condition
- Another target with a high offset is normally used, typically a scale bar target near object

Incorporation in a theodolite probe concept

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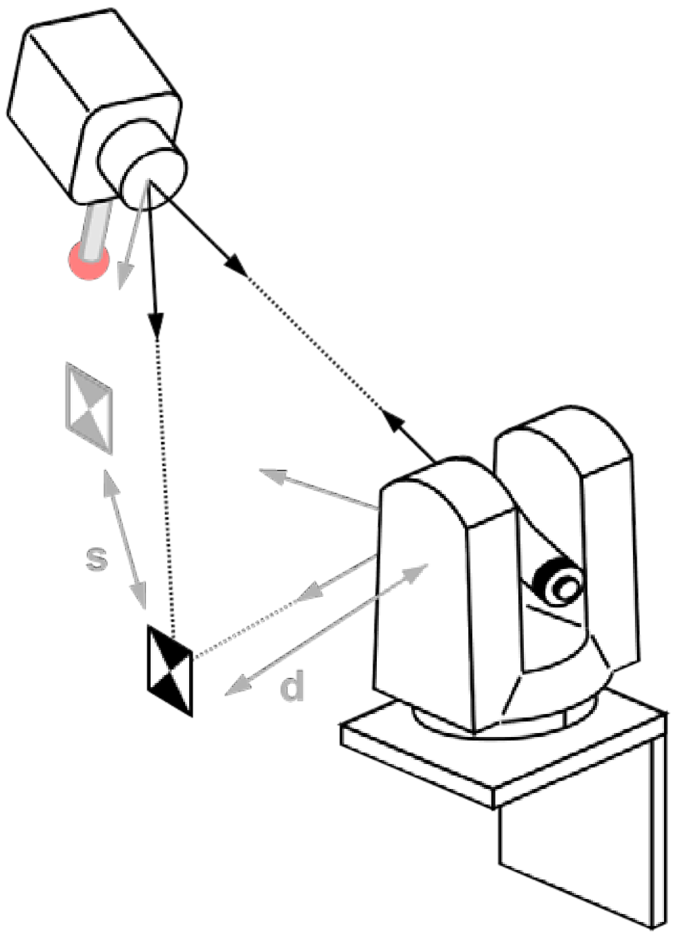
Stephen.Kyle@micronSpace.com
s.kyle@ucl.ac.uk



From concept by Kyle (1991) with probe stylus and ball added

- Concept
  - A fixed, motorized, (video) theodolite tracks a moving camera
  - Instruments have targets which identify their centres
    Example: 2 offset targets whose mean position is at the instrument centre
  - Scale by different methods:
    Example A: use scalebar of length s
    Example B: if theodolite is a Total Station make an initial range measurement d
- Extended concept
  - With added stylus and touch ball, camera becomes a 6DOF measurement probe

Equivalent tracker probe – Leica 2007patent

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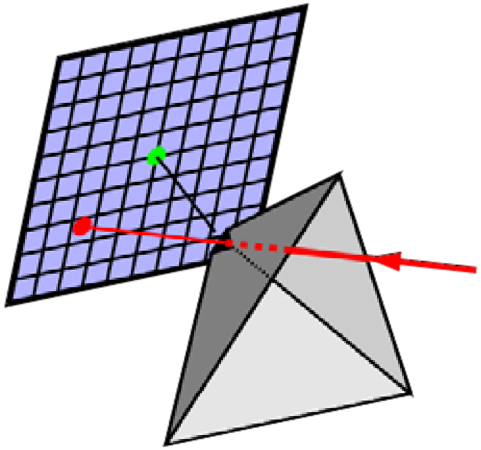
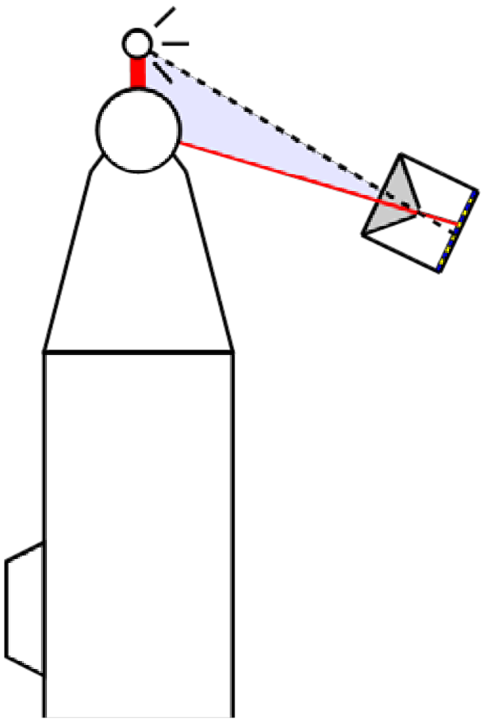
Stephen.Kyle@micronSpace.com
s.kyle@ucl.ac.uk

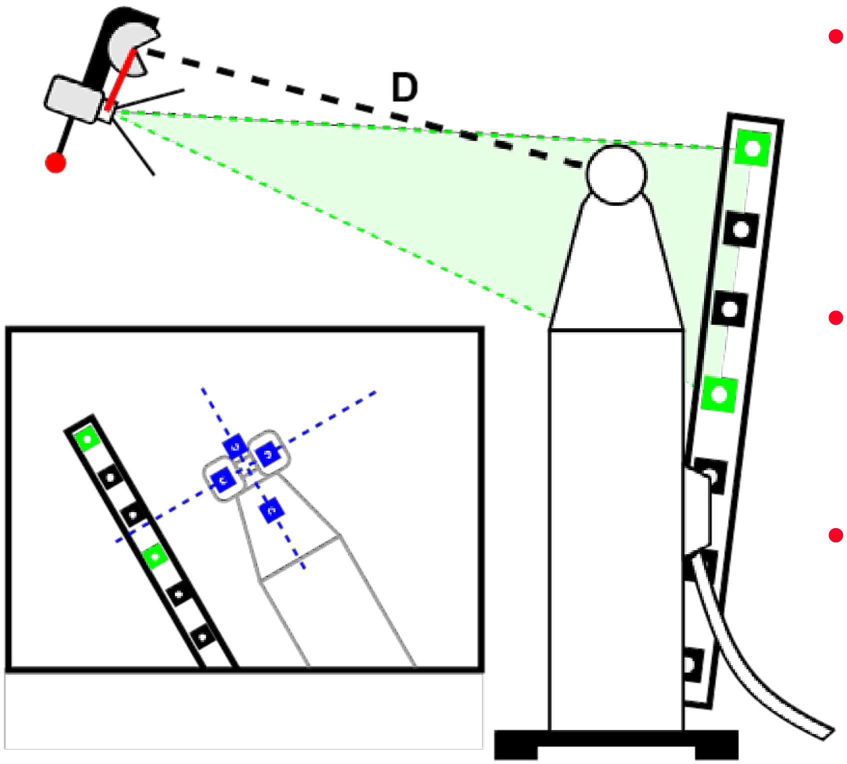




- Combi camera + target exists for laser tracker
  - Retro-reflecting prism has apex removed (a "pinhole prism" or "pinhole retro-reflector")
  - Part of tracker beam passes through the hole
  - Light sensing device (CCD or CMOS chip, PSD, etc.) offset behind hole
  - Equivalent to a combined pinhole camera + target reflector
- Leica 2007 patent
  - Offset luminous target attached to tracker is also recorded on image chip (not PSD)
  - Compared with theodolite concept, range here measured directly to "camera"
  - For optimal roll, configuration is lo-res/hi-offset so works best at close ranges where subtended angle at camera is largest

Variant tracker probe – Metronor 2006 patent

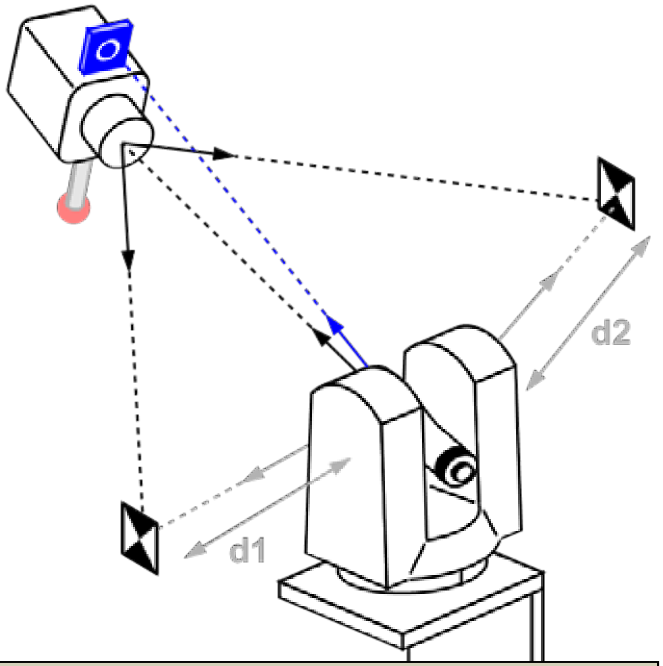
micronSpace
Stephen.Kyle@micronSpace.com
s.kyle@ucl.ac.uk

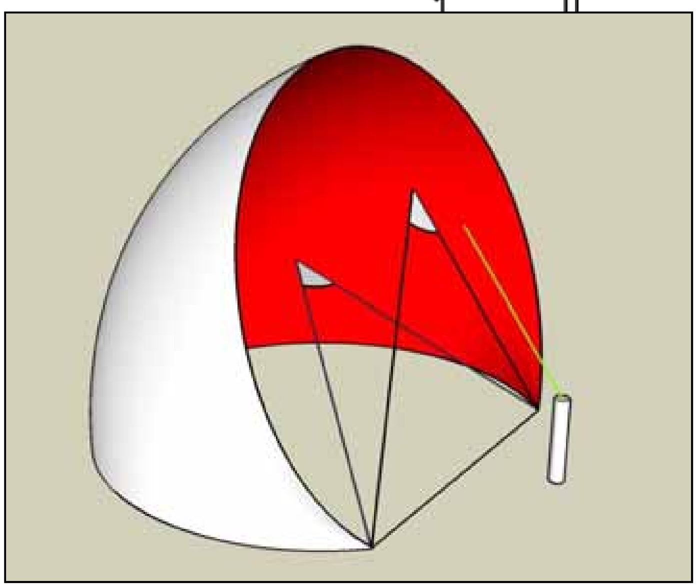


- Combi (pinhole) camera + reflector here replaced by separate camera + reflector
- No direct pointing from camera to tracker; use two offset targets instead (shown green, can be on or off tracker)
- Potential for camera/tracker pointing by use of multi-target combination (shown blue)
- Excess data is measured; tracker range D is not mathematically required (separation of offset targets gives scale)
- Again lo-res/hi-offset condition for optimal roll so best at close ranges if targets are attached or close to tracker

Probe without direct range measurement

micronSpace
Stephen.Kyle@micronSpace.com
s.kyle@ucl.ac.uk

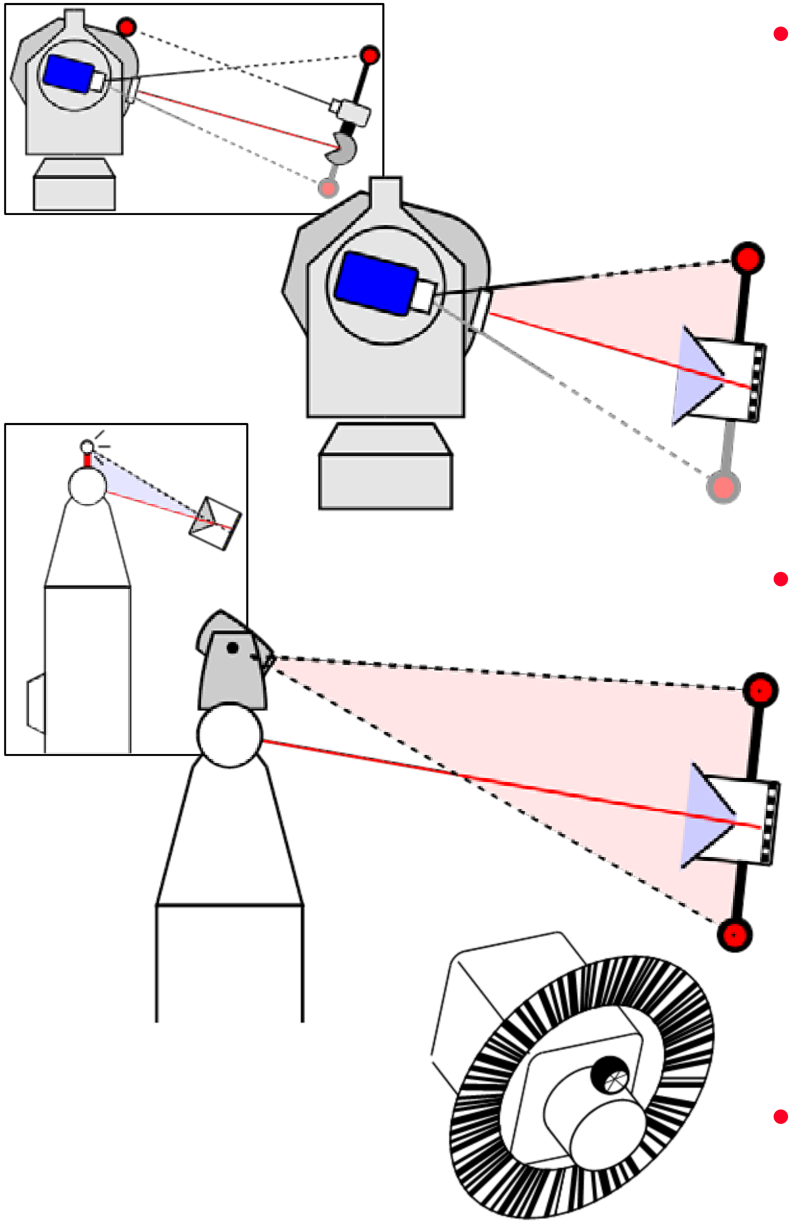




- An improved robot theodolite probe (upper diagram)
  - Theod. sights offset target attached to camera
  - Camera sights 2 fixed targets offset from theod.
  - Prior location of fixed targets by range measurements d1, d2 (e.g. use robot Total Station in place of motorized theodolite)
  - Equivalent to Metronor concept without direct range measurement between instruments
- 6DOF location (lower diagram)
  - Angle subtended at camera by fixed targets puts camera on arc of circle
  - Rotation of arc about chord (through targets) puts camera on surface shown
  - Every surface point is a 6DOF camera location
  - Ray from theodolite to camera (shown green) fixes camera's 6DOF

Roll targets on probe for camera on tracker

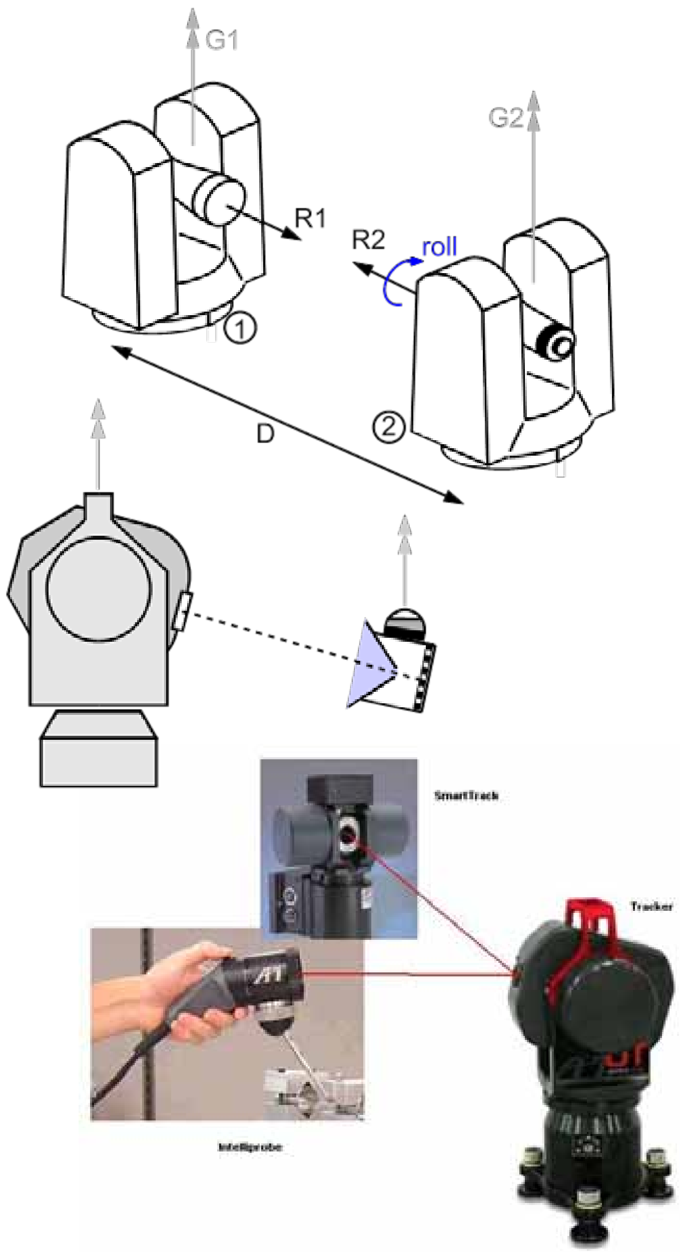
micronSpace
Stephen.Kyle@micronSpace.com
s.kyle@ucl.ac.uk



- CMSC 2005 concept
  - Camera on tracker (e.g. API's overview camera) views single offset target on pinhole prism
  - More targets improve accuracy
  - Inset diagram shows equivalent arrangement using camera + offset reflector at probe
  - Lo-res/hi-offset implies close range use
- Leica 2007 patent
  - Zoom camera on tracker (hi-res)
  - Two targets specified (good for accuracy)
  - Hi-res/lo-offset roll condition allows use over extended range
  - From inset diagram compare concept with target on tracker and camera at probe
- Consider alternative target, e.g. barcode, for improved roll measurement (CMSC 2006)

micronSpace
Stephen.Kyle@micronSpace.com
s.kyle@ucl.ac.uk

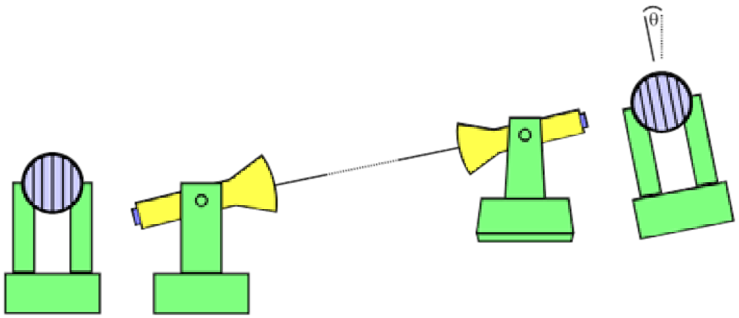
Roll by tilt sensing

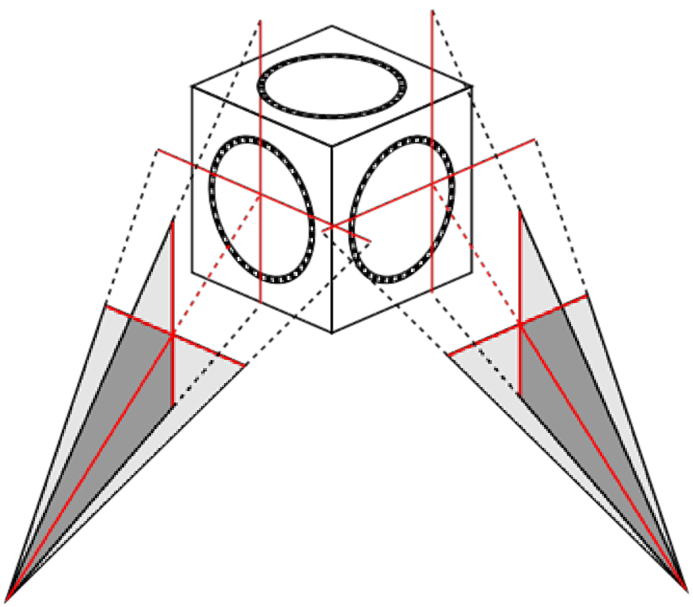


- Standard levelled theodolite orientation
  - Vertical Z axes (G1, G2), reciprocal pointing (R1, R2) and measured separation D, provide orientation (relative 6DOF)
  - G1, G2 equivalent to offset target at infinity
- Concept believed to be used in API IntelliProbe and SmartTrack (verbal confirmation only)
- Advantages of tilt sensing
  - No offset target required
  - Operates over full tracker range
- Disadvantages of tilt sensing
  - Limited roll range range for given accuracy
  - Dynamic effects cause delays, lower accuracy
  - Fails when measuring vertically

Roll by transmitted reference direction

micronSpace
Stephen.Kyle@micronSpace.com
s.kyle@ucl.ac.uk



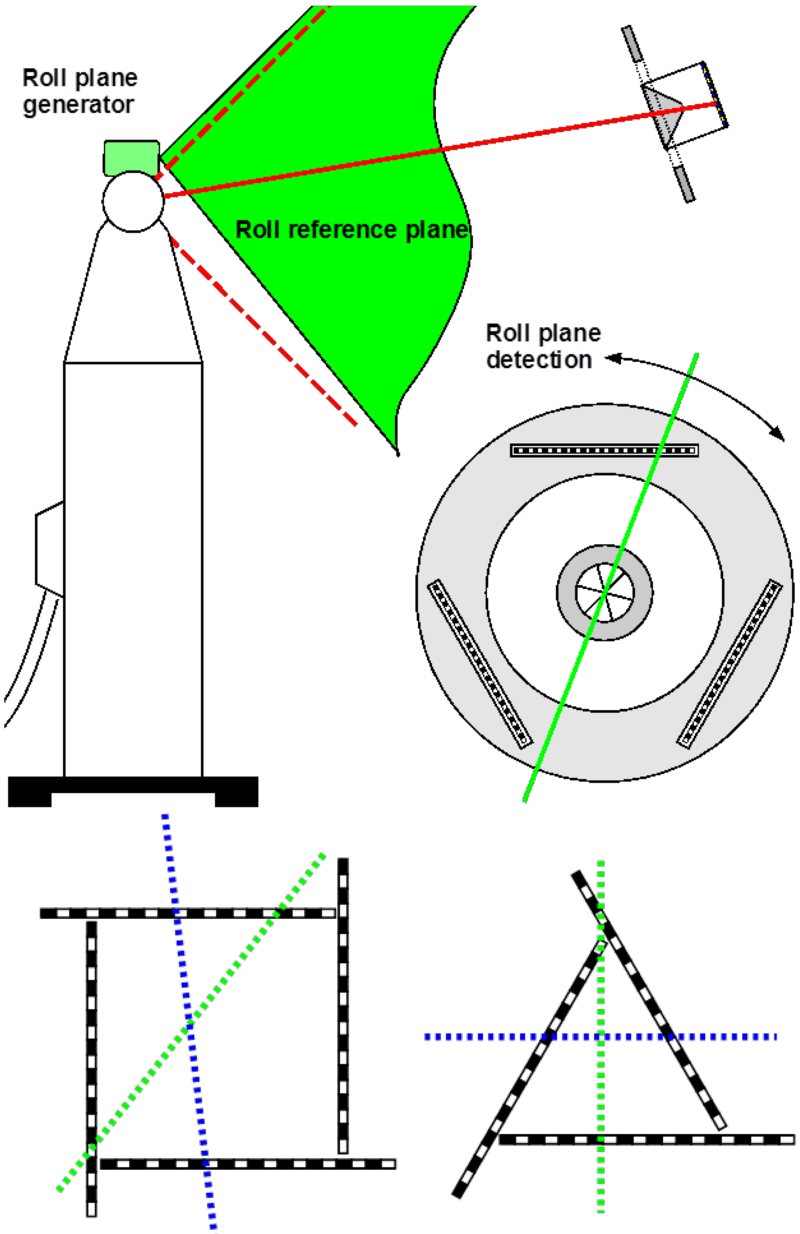


- A transmitted reference direction or pattern can be detected at the receiver and used as a roll reference direction
- Use of polarized light is a frequently mentioned mechanism appearing in many papers and patents (examples from NPL, Daimler Benz, API)
- 1990 concept (top diagram) suggests use in theodolite orientation

- Transmitted pattern could also be used.
- Example (lower diagram) is 1983 “Bird” concept
  - Dual-head triangulation system
  - Each head projects cross-shaped laser beam onto CCD ring sensors on probe
  - Strong roll information + variable strength pitch and yaw data from each image gives 6DOF of probe (Bird sensor = 3D mouse)

Roll reference plane – Leica 2007 patent

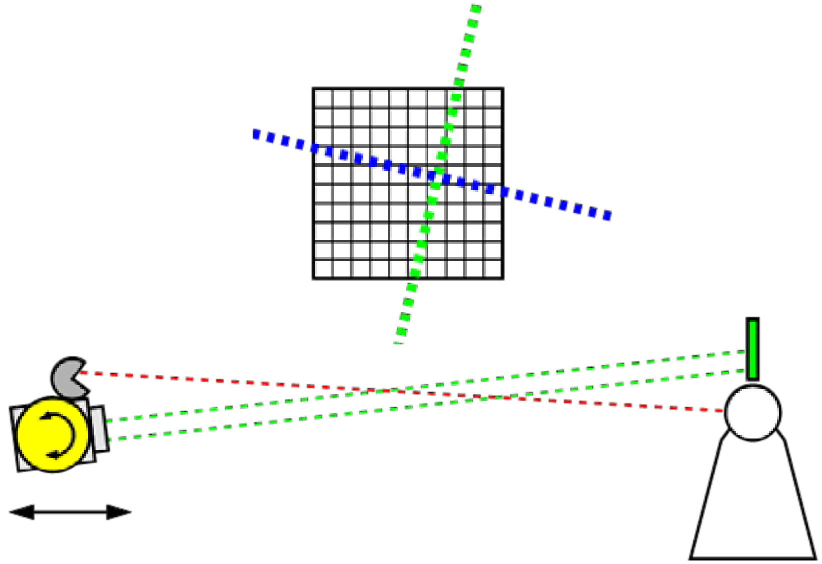
micronSpace
Stephen.Kyle@micronSpace.com
s.kyle@ucl.ac.uk



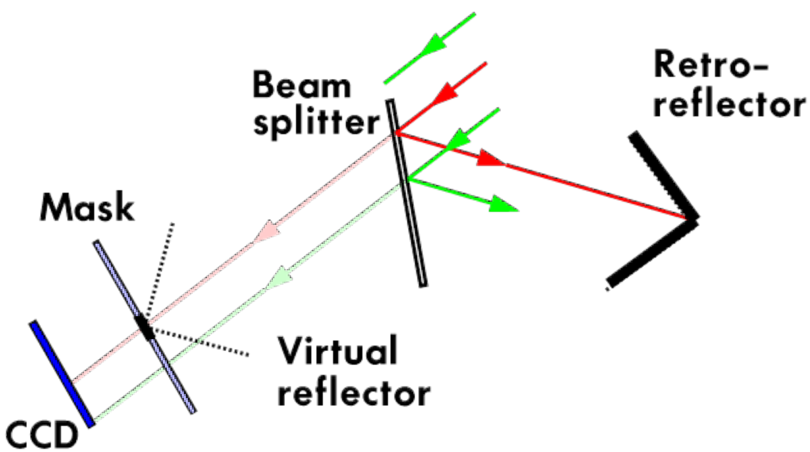
- The Bird system would require only one projected cross if the triangulation head could also measure range
- In comparison, Leica's 2007 patent shows a single projected roll reference plane, e.g. laser fan beam, intersecting one of several linear CCD arrays surrounding the retro-reflector (upper diagram)
  - Only one intersection necessary but more achieve higher accuracy
- Lower diagram shows alternative concept where multiple linear sensors simulate a higher resolution version of the Bird system's ring sensor and potentially enable more accurate roll measurement

Other roll pattern concepts

micronSpace
Stephen.Kyle@micronSpace.com
s.kyle@ucl.ac.uk



- As an alternative to linear arrays and ring sensors a CCD area array can detect a projected line or pattern, e.g. cross
- Project from probe to CCD on tracker
  - Intersection point of cross provides an offset from CCD centre, hence tracking mechanism to stay on target



- Project (co-axially) from tracker onto probe
  - Beam splitter at target reflector provides possible mechanism to filter out the roll pattern, here shown with a mask to obtain also pitch and yaw (CMSC 2006)
  - Generating a suitable roll pattern might be a challenge

Conclusions

micronSpace
Stephen.Kyle@micronSpace.com
s.kyle@ucl.ac.uk

- Separate measurement of roll from pitch + yaw could improve angular orientation accuracy of a 6DOF tracker probe and enable, for example, use of a longer stylus

- For hand-held probes roll methods worth investigation include:
  - Projected pattern from tracker onto probe
  - Optimized imaging at tracker of targets at probe
  - All-angle tilt sensing with compensation of dynamic effects

- For motorized probes possibly consider
  - Use of polarized light
  - Projecting roll planes and patterns from probe to tracker
  - Use of space triangle with wider target spread in tracker space