Background

• Engineering Photonics - Instrumentation development research centre at Cranfield University

• Broad research portfolio: Fibre optic sensors, optical gas sensing, optical flow measurement, optical interferometric NDT

• Wide range of application areas: manufacturing, transport, environmental technology, energy, agrifood, healthcare.

• EPSRC supported research into Novel Manufacturing Instrumentation (Grant number: EP/M020401/1)
Background/Outline

• **Aim:** To develop new positioning instrumentation to improve flexibility and precision in robotic manufacturing …

… overcome limitations in mechanical stiffness, process/environmental disturbances and kinematics errors

… however also applicable in other areas

• Primarily focused on two complimentary optical measurements techniques

  **Range-resolved interferometry (RRI)**

  **Laser speckle pattern correlation (LSC)**

• Combination for multi-parameter relative positioning sensor:

  **Workpiece Positioning sensor (wPOS)**
Range Resolved Interferometry (RRI)
Range Resolved Interferometry (RRI)

• A novel interferometric technique, using optical-frequency modulation

• Complexity in the electronics instead of optics

• Uses standard telecoms industry laser diodes & optical fibre components - cost-effective and compact

• Combined interferometric measurements and absolute ranging

• Allows signals from multiple sources to be distinguished by range
RRI operating principle

RRI operating principle

OPD: Optical Path Difference

RRI operating principle

Demodulate signal → using complex carrier calculated at the range

Range Resolved Interferometry (RRI): Ranging Mode

- **Absolute** range measurements
- Signal amplitude evaluated at different ranges $\rightarrow$ peak fitting yields range
- 10 to 50 µm resolution at kHz data rates
- Large dynamic ranges ($>>$ 10 cm)
- Multiple (semi-transparent) objects can be measured simultaneously
- Can be thought of as a low-resolution, high-dynamic range Optical Coherence Tomography (OCT) technique
Range Resolved Interferometry (RRI): Phase Evaluation Mode

Interferometric signal from single range

- **Relative displacement** measurements
- Nanometre resolutions at kHz data rates
- Evaluated for a single reflection or for multiple surface

Phase evaluation yields relative displacements
Applications of RRI

In-process layer height measurements

- Appropriate Resolution (10 to 50 µm)
- **Inherently insensitive to arc light**, allows measurement close to welding torch
- Compact fibre-coupled measurement head
Applications of RRI

In-process measurement through laser processing head

• Collaboration with Welding and Laser processing centre (Cranfield)
• Integrate CO-RRI sensor in the view port of the welding head to be coaxially aligned with laser beam
• Explore different applications for CO-RRI in laser processing. E.g. active focus control, topography measurements during welding)

Co-axial measurement calibration
Applications of RRI

Topography of beer can lid during processing

10x Faster (no processing beam present)
Applications of RRI

Multi-dimensional positioning via single Interferometer

- Components separated by optical path difference
- 2 or 3 dimensions with additional out-of-plane beam

TOP-DOWN VIEW

Beamsplitter cube

Fibre collimator

Nanocube stage

X Direction of stage travel

Y

Resultant RRI Signal

To Interrogation Hardware

Optical Path Difference
Laser Speckle Correlation (LSC)

- Object illuminated by coherent light
- Scattered interference pattern recorded by array detector/camera
- Interference from points on optically rough surface leads to characteristic ‘speckle pattern’
- **No imaging – objective speckle**
- Speckle size determined by spot size rather than aperture → better signal
- Speckles form from any optically rough surface including: unpolished metal, paper, card, rock
Laser Speckle Correlation: Principle

- Tracking changes between speckle patterns used to determine object deformation

**Pattern translation:**
from object translation, tilts and strains

**Pattern rotation:**
from in-plane rotation
Laser Speckle Correlation: Principle

1. Acquire reference image
2. Acquire new frame
3. Cross-correlation
4. Speckle shift: \((A_x, A_y)\)
5. Pre-calibrated scaling factors (ratio of speckle shift to object translation)
6. Calculate position & velocity
7. Position: \((x, y)\)
8. Velocity: \((v_x, v_y)\)
9. Check reference limits
10. Store as reference image

Reference image
Current image

cross correlation
Applications of LSC

Robotic tool speed sensor

- Robot (uncompensated)
- Robot (compensated)
Applications of LSC

Robotic tool speed sensor

- Circular motion at fixed speed 1mm/s
- Accuracy:
  - <0.01 mm/s (@ Working distance)
  - <0.025 mm/s (WD ± 5mm)
  - <0.5 mm/s (x50) with ±5° misalignment
- Measurement range: ±0.01 - 70 mm/s (current system max.)
- Precision: 3σ: ±0.15 mm/s → position error 0.3µm → 0.06 pixels
- Limited by peak fitting accuracy

Applications of LSC

Robot path characterisation - Large displacements (m’s)

- Example of paths measured using the LSC technique on KUKA KR150 L110-2 robot
- Multiple repeat measurements of same path shown.
- Accumulated error ~120 µm after ~0.5m travel
- Mostly due to misalignment between robot xy plane and build plate.
- Accuracy over shorter ranges much higher...
Applications of LSC

Small displacements (mm’s)

E.g. robotic drilling of high relative accuracy component mounting holes at lower absolute position accuracy of robot or Vibration monitoring

- Translation stage / Aluminium sheet
- ±100µm displacement
- Accuracies <0.5µm
- Improved peak-fitting ~10’s nm seems possible

Object motion tracking/stabilisation

- No need for key-points/ markers
- Higher update rate than visual servoing

In-plane rotation

- Work-in-progress
- Accuracies of < 0.01^o over ±10^o range
Workpiece Positioning Sensor (wPOS)
Aim: a new, widely applicable, end effector mounted, real-time, three degree-of-freedom position sensor

- RRI absolute range (out-of-plane) measurement
- LSC relative in-plane measurement
- RRI range measurement used to correct LSC scaling factors
wPOS: Development System

Signal processing unit
- 19” rack mounted unit.
- Containing lasers, PSUs and control & processing PC.
- Armored optical fibre delivery to sensor head

Range-resolved interferometry
- 1550nm telecoms diode and driver
- Hi-speed ADC and FPGA signal processing

Laser speckle correlation
- Fibre-coupled diode laser, 658nm, max output 50mW, typical 0.5mW
- USB3.0 CMOS industrial camera & laser line filter
**wPOS: Example results (6 DoF stages)**

**1 mm Δz step change**
- <15 μm xy accuracy
- 0.75 m travel

**1 mm Δz gradient**
- <30 μm xy accuracy after 0.75 m travel
- Worse due to offset between RRI & LSC beams
wPOS: Example results (Igus 5 DoF Arm)
Conclusions

• Two optical techniques for position/displacement measurements
• Combined three-degree of freedom sensor
• Application examples and potential areas of application

Future directions

• Further instrumentation development and improvements
  • Fully characterize positioning performance of wPOS system
  • Addition of further degrees-of-freedom
• Application based trials ...

Acknowledgements

Engineering and Physical Sciences Research Council (EPSRC) UK
[grant numbers EP/M020401/1, EP/N002520/1]

Welding Engineering and Laser Processing Centre, Cranfield University for collaborations involving the WAAM process.