Multicopter Workshop – Manchester, Monday 9 July 2018

University of Strathclyde Engineering

Autonomous Drones for Next Generation Visual Inspection

Professor Gareth Pierce, Dr Gordon Dobie, Dr Charles Macleod, Dr Kenneth Burnham, Dayi Zhang, Robert Watson, William Jackson, Liam McDonald, Daniel McMahon

AFRC ADVANCED FORMING RESEARCH CENTRE UNIVERSITY OF STRATHCLYDE

RCNDE UK Research Centre in NDE

NATIONAL NUCLEAR LABORATORY

CUE

Department of Electronic & Electrical Engineering
Centre for Ultrasonic Engineering

EDF ENERGY

A brief history of robotics research in CUE

University of Strathclyde Engineering

- 2006 – SGP joined CUE to work on robotics for NDE (non-destructive evaluation)
- Numerous projects run through RCNDE
  - **Mobile robotics**, leading to commercialisation with Eddyfi / Silverwing (Oil and Gas) and Nuclear site inspections
  - **Manufacturing robotics**, leading to scale up and commercialisation through AFRC and aerospace partners
- **Identified need for accurate positioning and data registration as essential for robotic NDE and inspection**
- 2009 - Established FIRST laboratory to support NDE research:
  - Enabled state of the art positioning equipment to be purchased (VICON and Leica Laser Tracker) – allows accurate 6DOF positioning measurements to be performed
  - Wheeled robotic platforms and UAV research
  - Manufacturing robotics (6/7 axis systems)

Robots used as a delivery platform, for NDE and other sensing, including metrology

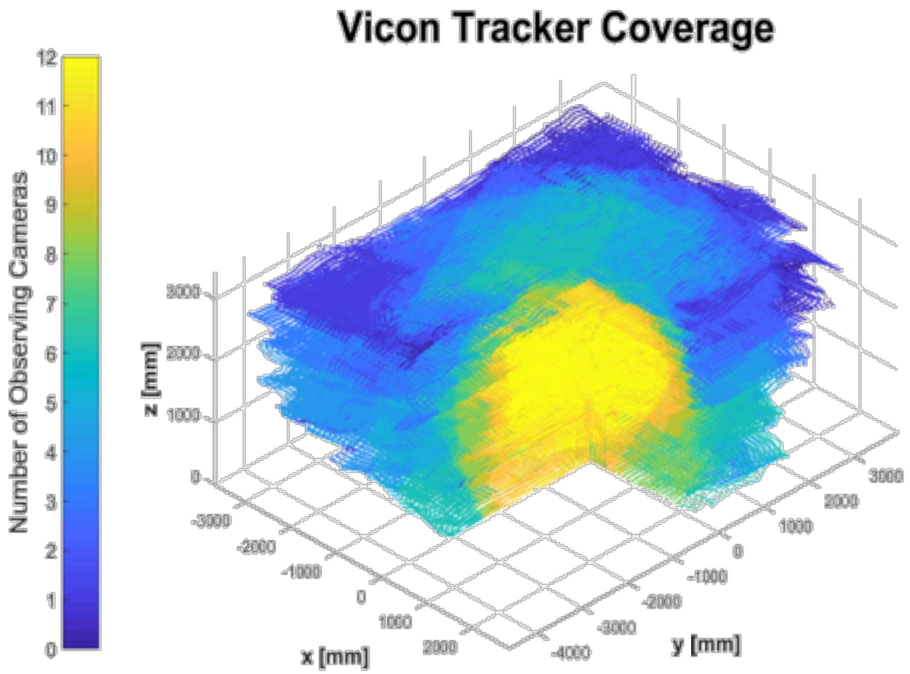
RCNDE
UK Research Centre in NDE

Indoor Positioning Systems

Verification of tracking algorithms

Vicon Motion Tracker

- Operating Principles
  - 12 cameras bound tracking volume
  - Infra-red retroreflectors mounted on object
  - Reprojection and triangulation of markers from image planes
- Volume Coverage
  - Physical assessment
  - Correlation to accuracy
- Modelling
  - Interpretation of calibration output
  - Camera observability projection



Leica AT901B Laser Tracker

- Operating Principles
  - 2 axis rotary position encoder
  - Absolute Interferometer Module (AIFM)
  - Directional retroreflective sphere
  - Accuracy of ±(15 µm + 6 µm/m) over 80 m radius

1. Vicon T160 Camera, Available: http://mars.cs.umn.edu/images/research_platforms/vicon-1.png, Accessed: 05/12/2017

Robotics, Automation & Inspection: THEMES

Flexible robotics
Integrated inspection

Inspection for High Value Manufacture

Autonomous inspection to reduce cycle time for aircraft production (A32x, 737 series)

Autonomous inspection for high volume low cost automotive remanufacture

Inspection for Remanufacture

Inspection for Additive Manufacture & Materials Joining

In-process inspection for additive manufacturing and material joining

Flexible programming for multiple robot platforms

UAV control and path planning for asset inspection

Asset Inspection & Decommissioning

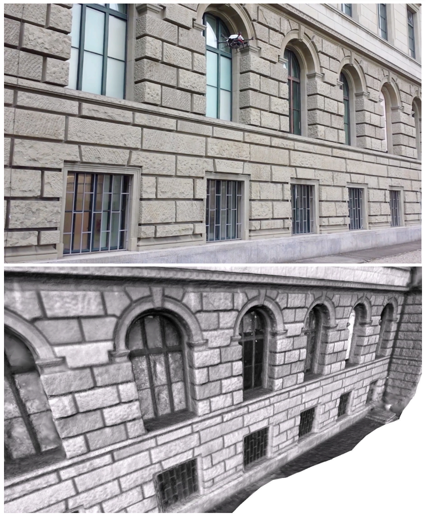
Autonomous inspection for hazardous environments

Large data volumes

UAV Inspection Applications

Driven from RCNDE partners

- Buildings, civils
- Nuclear applications
  - Civil
  - Storage
- Wind turbine
- Offshore, oil and gas
- Power distribution networks
- Aircraft routine inspection



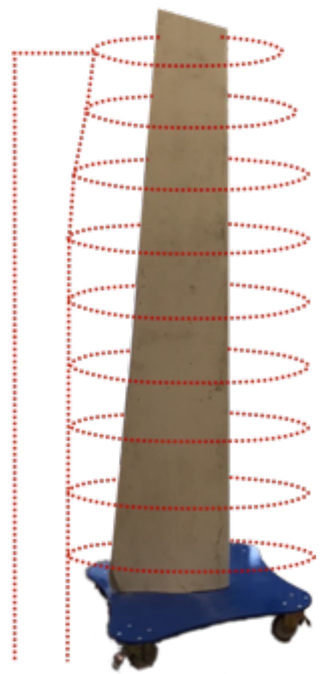
S. Omari, P. Gohl, M. Burri, M. Achtelik, and R. Siegwart, "Visual industrial inspection using aerial robots," in *Proceedings of the 2014 3rd International Conference on Applied Robotics for the Power Industry*, 2014, pp. 1–5.

Autonomous visual navigation of Unmanned Aerial Vehicle for wind turbine inspection by: Martin Stokkeland, Kristian Klausen, Tor A. Johansen, 2015 International Conference on Unmanned Aircraft Systems (ICUAS).

UAV Inspection Approach

- Feasibility study with EDF Energy, AFRC and GAIA Wind
- Using pre-planned flight path (not fully autonomous)
- Use 3D reconstructed model for an overview of the surface while conventional UAV scan provides individual pictures

- 3.1m height
- 386mm wide (top); 619mm wide (bottom)



- Circular around the blade
- Radius of top circle: 1150mm
- Radius of bottom circle: 1250mm
- Auto Take-off and landing

Reference model comparison

University of Strathclyde Engineering

- *GOM ATOS Triple Scan* used to capture reference standard model of the blade
- Initially used manually captured images and used Agisoft Photoscan to build 3D mesh model of blade
- Validated performance of model meshing without the influence of the delivery platform

Camera alignment

- Sparse point cloud

Dense point cloud →

- Estimated camera positions

Mesh →

- 3D polygon of object surface

Comparison of visual profile with 3D reference model

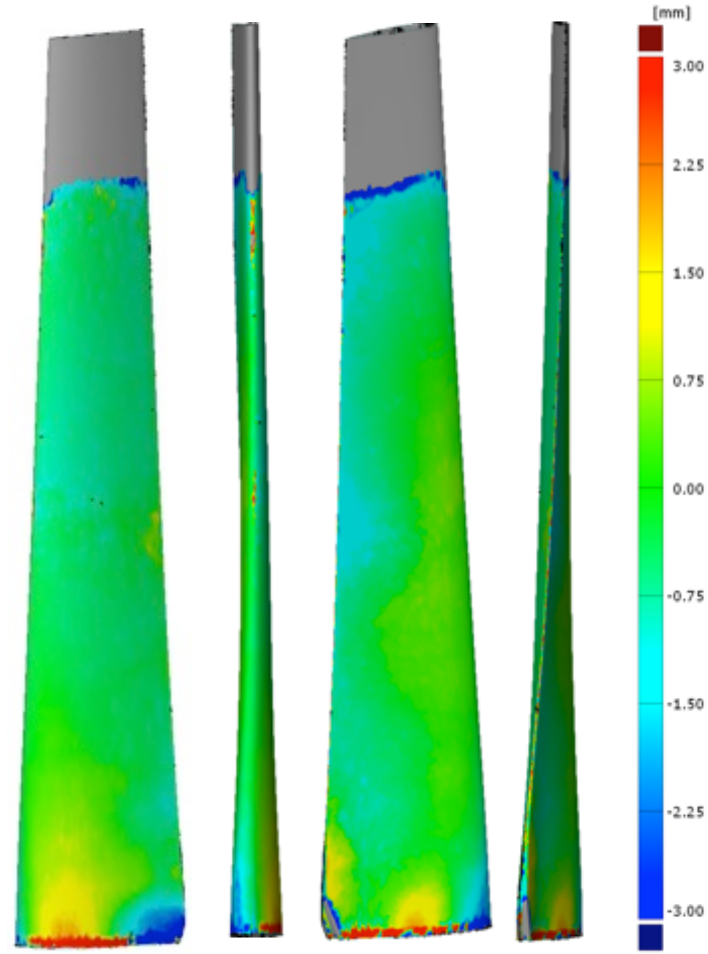
Visual Reconstruction

Alignment

3D Reference Model

GOM Inspect

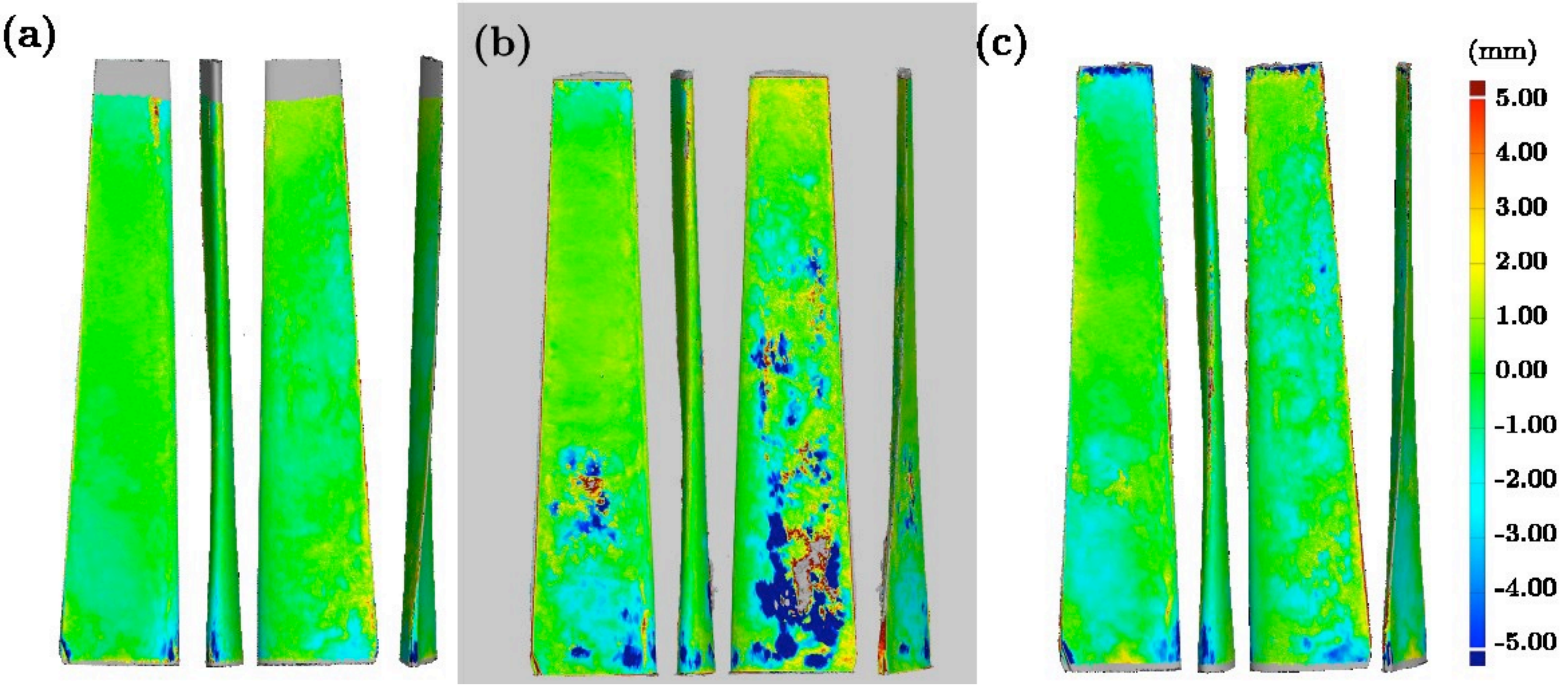
Deviation Map



Verifies performance of meshing algorithm… now use UAV platform to acquire data

UAV Blade scan - video

UAV blade scan - effect of lighting and shutter speed

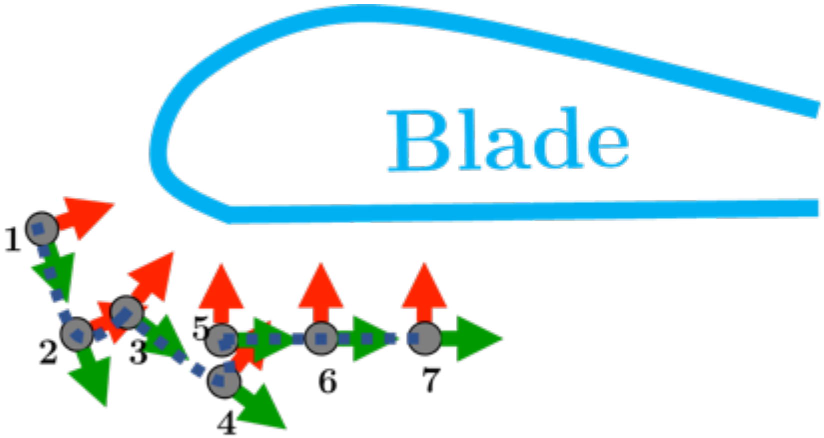


Deviation maps of the reconstructed model captured in different light intensity (a) 30 ms shutter with extra light, (b)30 ms shutter ambient light, (c) 60 ms shutter ambient light

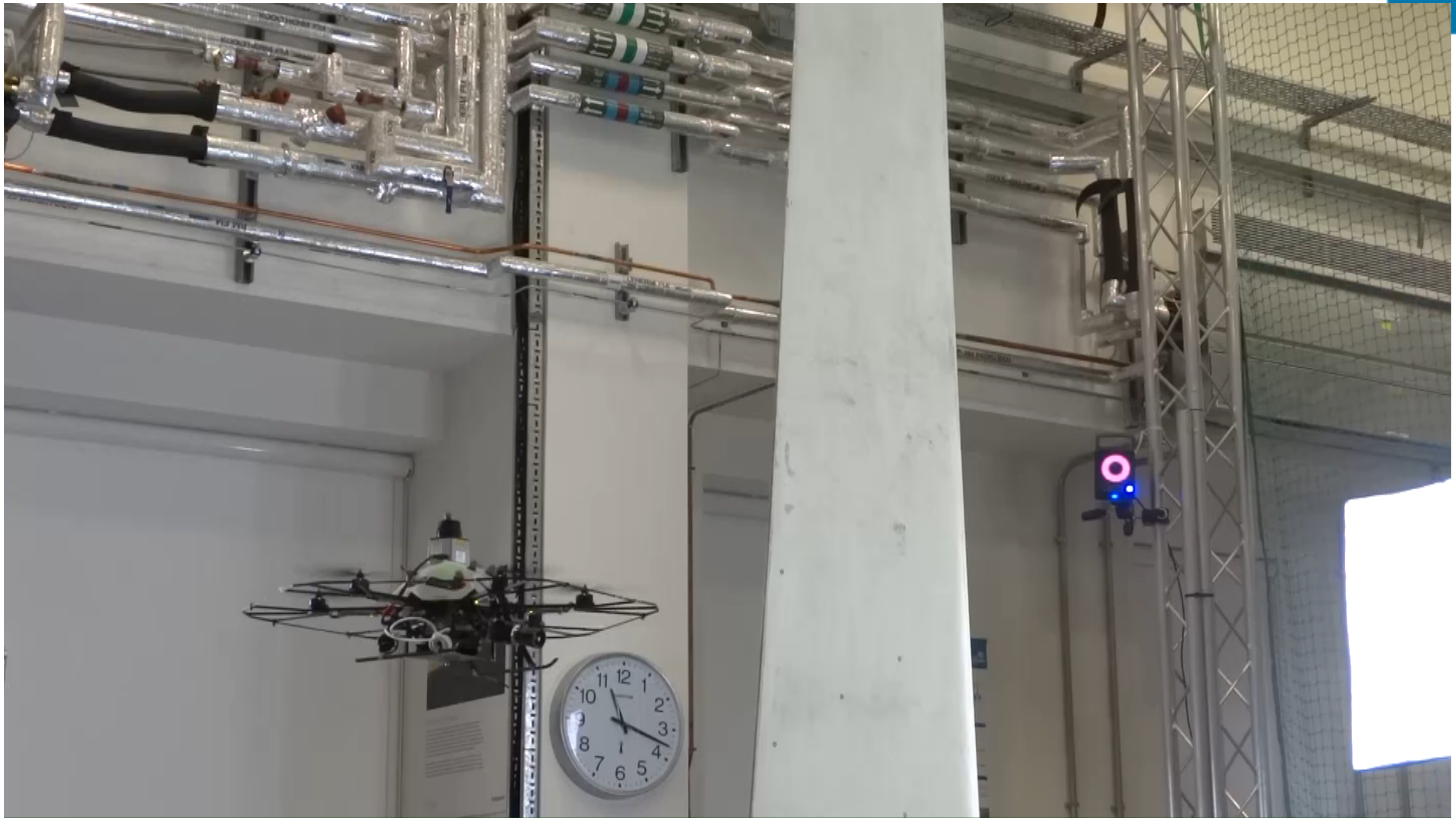
	30 ms shutter Extra light	30 ms shutter Ambient light	60 ms shutter Ambient light
Standard Deviation (mm)	1.56	2.46	1.97
Mean Error (mm)	0.3853	0.6493	0.4571

Laser Scanner for Alignment

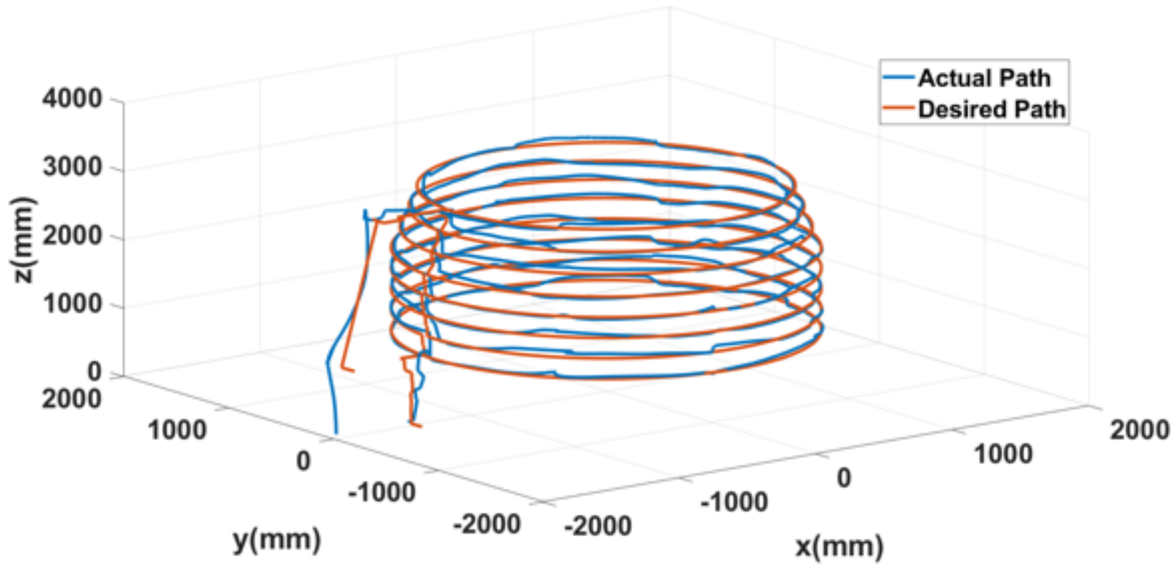
- A laser scanner (*Hokuyo URG-04LX*) is mounted on top of the UAV measure the alignment error and displacement from target
- The distance measurements maintain the UAV in a constant offset and optimise the camera focusing.
- Allows UAV trajectory to follow the blade geometry.



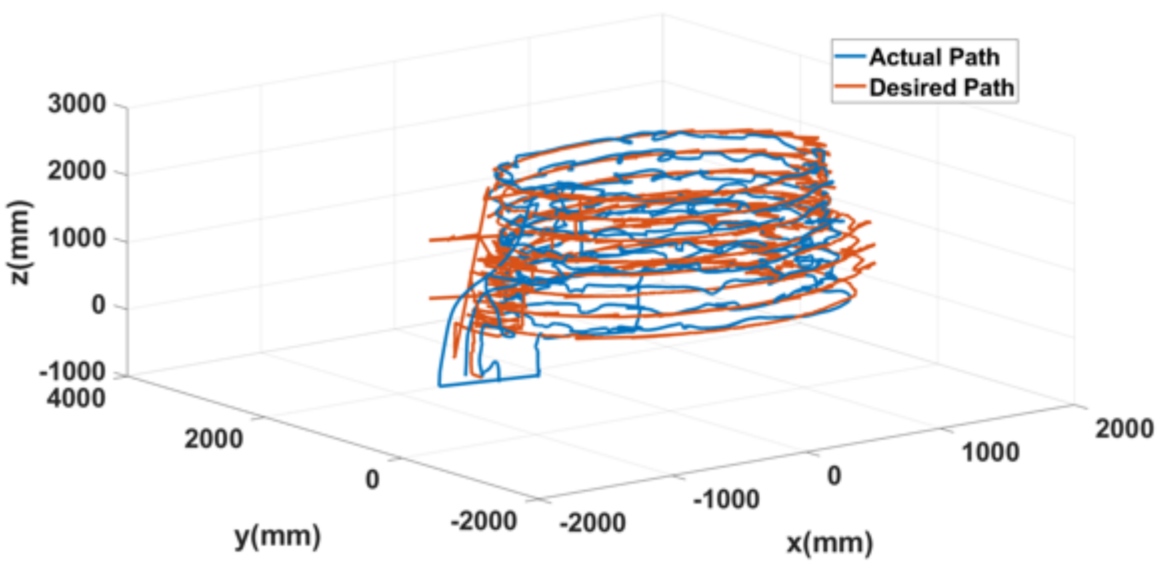
Laser Scanner for Alignment



UAV Flight Path



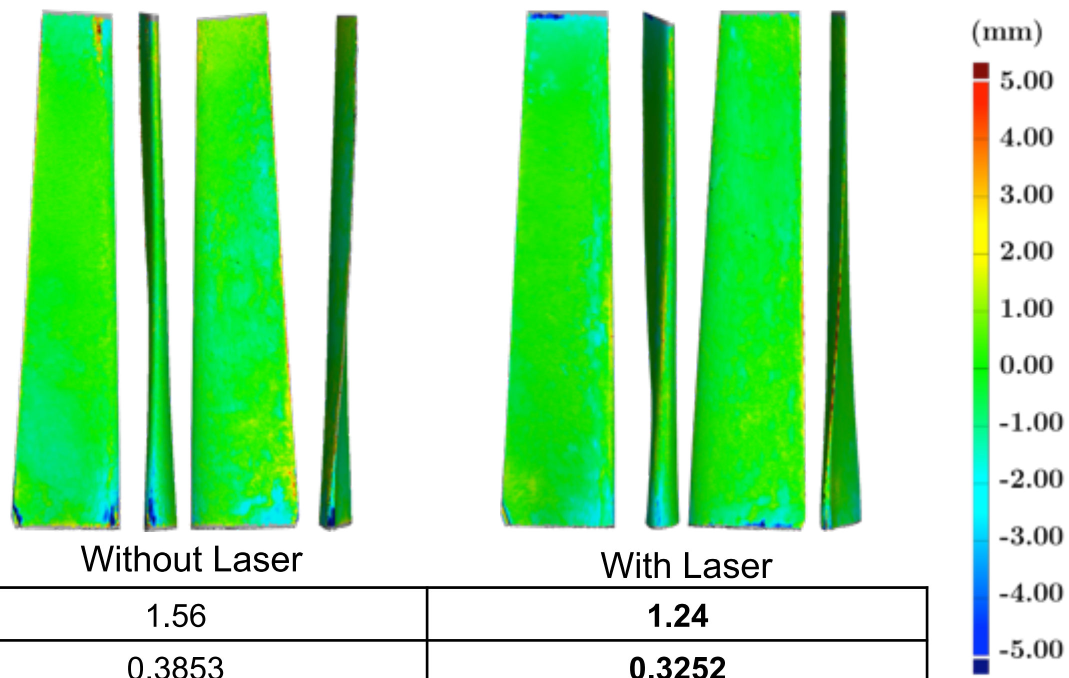
Prior defined path



Laser compensated path

Results with/without Laser
Deviation Map Comparison

Results without laser reconstruction come from images with circular flight path. The camera is 30ms shutter time and with external lights.



Standard Deviation (mm)	1.56	**1.24**
Mean Error (mm)	0.3853	**0.3252**
Peak to Peak Error (mm)	13.56	**5.71**

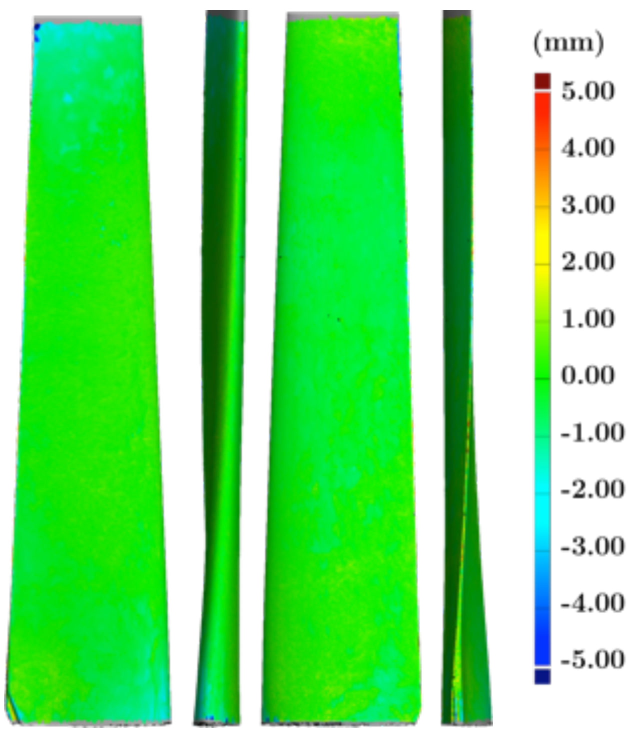
Results with/without Laser
Texture Comparison

Without Laser

With Laser

Improvement in focal performance with maintaining constant stand-off distance

Results with Laser Scanner
Filtered Images



- The camera captured multiple images in the similar poses.
- The results are based on the set of images with laser scanner. And the local best images are selected and imported to the software for the reconstruction.

	Original	**Filtered**
Standard Deviation (mm)	1.24	**1.20**
Mean Error (mm)	0.3252	**0.2282**
Peak to Peak Error (mm)	5.71	**4.27**

UAV platforms for research

Commercial options

Commercial Review

1.

2.

3.

	AscTec Firefly	DJI Matrice 100	Intel Aero
Configuration	Hexacopter	Quadcopter	Quadocpter
Dimensions	605 x 665 x 165 mm	510 x 510 x 342 mm	360 x 360 x 222 mm
Max Take Off Weight	1.6 kg	3.6 kg	1.9 kg
Payload	600 g	1245 g	580 g
Flight Time (Unladen)	22 min	40 min (w/ 2 Batteries)	20 min
Max Airspeed	15 m/s	22 m/s	15 m/s
Wind Resistance	10 m/s	10 m/s	7.7 m/s
Weather Proofing	Poor (Basic Canopy)	None	None
Batteries	LiPo 3S 4900 mAh	LiPo 6S 5700 mAh	LiPo 3S/4S (Sold Separately)
Flight Control Software	AscTec Autopilot	DJI N1	Pixhawk
Developer Level Software Access	Yes	Yes (DJI SDK)	Yes
Cost (airframe only)	£5,007	£1,427	£1,100

1. AscTec Firefly, Available: http://wiki.asctec.de/download/attachments/4816978/Firefly.jpg?version=1&modificationDate=1407933353000&api=v2 , Accessed: 05/12/2017
2. Intel Aero, Available: https://docs.px4.io/assets/hardware/intel_aero/intel-aero-rtf.jpg, Accessed: 04/12/2017
3. DJI Matrice 100, Available: http://www.dronenerds.com/media/product/8cb/dji-matrice-100-ready-to-fly-bundle-kit-with-guidance-system-flir-xt-640-30hz-camera-matricext640-30hzkit-dji-a8c.jpg, Accessed:15/12/2017

Strathclyde UAV Research Platform
New ICASE project RCNDE

Custom built inspection UAV

- Open source flight controller
  - Pixhawk 2.1 Cube
  - Px4 software
- Key design points
  - High payload
  - Extended flight time
  - Indoor and outdoor operation
  - Open source
  - Protective rotor guard

	Custom Built
Configuration	Quadcopter
Dimensions	900 x 900 x 430 mm
Max Take Off Weight	9.92 kg
Payload	2000 g
Flight Time (Unladen)	35 min
Weather Proofing	Avergage (Fully Enclosed)
Batteries	LiPo 6S 8500 mAh
Flight Control Software	Pixhawk
Developer Level Software Access	Yes (Complete)
Cost (airframe only)	£1,300

Strathclyde UAV Research Platform

New ICASE project RCNDE

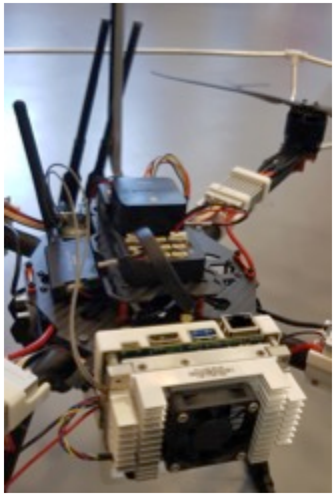
University of Strathclyde Engineering

Vicon external position measurement

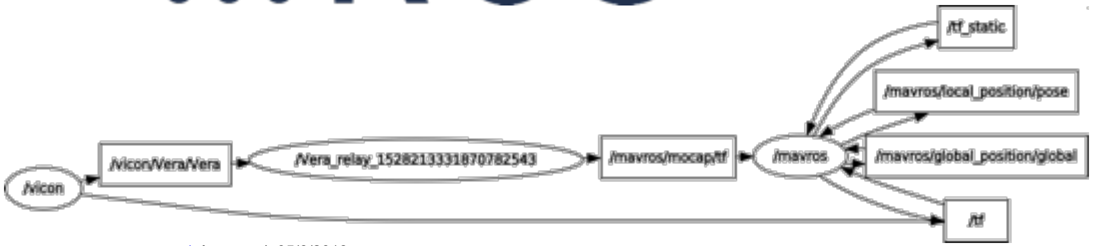
- Nvidia Jetson TX2 companion computer
  - Connectech Orbitty carrier board
  - Small form factor
  - Low power consumption
- Robotic Operating System (ROS)
  - Infrastructure for mobile robotics
  - Consistent and powerful toolset across numerous robotics platforms

1.

	Jetson TX2
GPU	NVIDIA Pascal™, 256 CUDA cores
CPU	HMP Dual Denver 2/2 MB L2 + Quad ARM® A57/2 MB L2
Video	4K x 2K 60 Hz Encode (HEVC) 4K x 2K 60 Hz Decode (12-Bit Support)
Memory	8 GB 128 bit LPDDR4 59.7 GB/s
Display	2x DSI, 2x DP 1.2 / HDMI 2.0 / eDP 1.4
CSI	Up to 6 Cameras (2 Lane) CSI2 D-PHY 1.2 (2.5 Gbps/Lane)
PCIE	Gen 2 | 1x4 + 1x1 OR 2x1 + 1x2
Data Storage	32 GB eMMC, SDIO, SATA
Other	CAN, UART, SPI, I2C, I2S, GPIOs



2. ROS



1. Nvidia Jetson TX2 Technical Specs, Available: https://www.nvidia.com/en-us/autonomous-machines/embedded-systems-dev-kits-modules/, Accessed: 05/6/2018
2. ROS Logo, Available: http://www.ros.org/press-kit/, Accessed: 05/06/2018

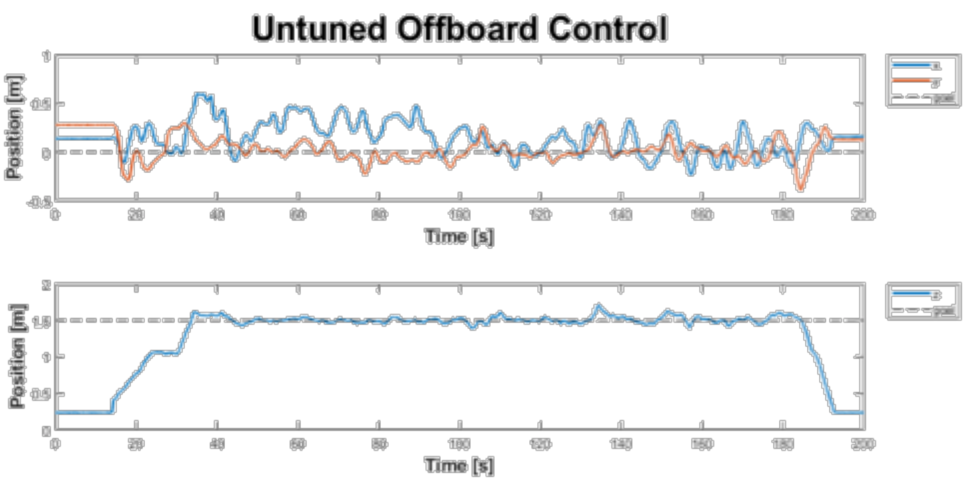
Strathclyde UAV Research Platform

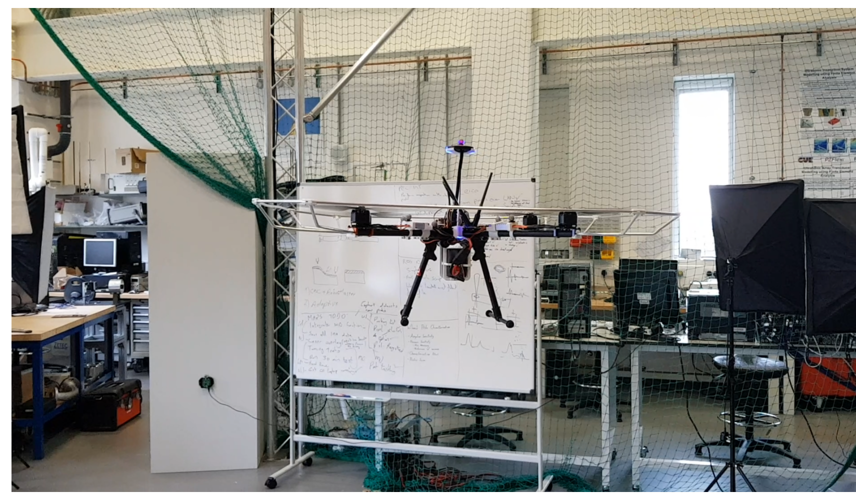
New ICASE project RCNDE

Offboard Control

- Preliminary results of software infrastructure testing
  - Using generic quadcopter PID controller
  - Proof of concept

Quantity	x	Axis y	z
Mean Error [m]	0.1581	0.0172	0.0072
Root Mean Square Error [m]	0.2417	0.0922	0.0614
Standard Deviation [m]	0.1828	0.0906	0.0610

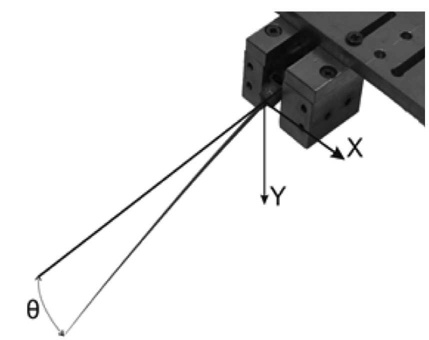




Next Steps
New sensors and control

- Vicon accuracy study
  - Comparative assessment with Leica tracker ground truth – improve accuracy of lab measurements
- Offboard control
  - Tune controller
  - Implement ROS node for arbitrary complex paths
- Ultrasound from a UAV
  - Mount wheel probe
  - Scan planar structures
  - Move to complex geometries
- Whisking sensors
  - Contact based
  - Collaboration with Bristol Robotics Lab
- Real Time Kinematic GPS
  - Integration and assessment

1.



1. Here+ RTK GPS KIt, Available: https://cdn8.bigcommerce.com/s-xkoep7/images/stencil/1280x1280/products/1300/7573/Here___80503.1501686285.jpg?c=2&imbypass=on, Accessed:10/01/2018

Next Steps
Environmental performance evaluation

New LVV Laboratory located at Sheffield Business Park next to Factory 2050

- The Structural Dynamics Laboratory for Verification and Validation (LVV) is a major new acoustics and vibration testing facility funded by EPSRC, the European Regional Development Fund (ERDF) and the University of Sheffield.
- The facility provides a unique research offering to academia and industry. In addition to allowing dynamic testing of full-scale structures in ambient laboratory conditions, the LVV offers the opportunity to test substantial structures, sub-structures and components in realistic environments.
- LVV will allow full environmental testing of new autonomous systems and control approaches developed through EPSRC funded AIMaReM project.

The University Of Sheffield.

EPSRC
Engineering and Physical Sciences Research Council

European Union
European Structural and Investment Funds

The LVV comprises of:

Three large, individual climatic test rooms allowing simulation of temperature, humidity, wind and rainfall effects. One room contains a 3.2m x 2.2m integrated Multi Axis Shaker Table (MAST). Further electrodynamic vibration systems allow a flexible range of testing to be conducted both within and outside the climatic test rooms.

A precision glass-sided wave tank with double flap wave generator (12m long, 1.5m deep) enabling simulation of deep water conditions. A strong floor (16m long x 3.5m wide) and wall (3m tall x 3.5m wide) enabling the testing of large components and structures in a range of mounting configurations.

Flexible laboratory space suitable for a broad range of dynamic testing at ambient temperatures (approx. 12m x 12m).

Conclusions

Many opportunities for collaboration

- Robot path planning and control
  - Pre-planned flight paths
  - Laser ranging/ scanner in flight control
  - ROS platform integration
- Surface geometry measurement
  - Using visual data and photogrammetry reconstruction (bith commercial tools and research approaches)
- 3D high precision positioning
  - Calibrated 3D metrology capabilities – allows new control algorithms to be evaluated
  - LVV facility at Sheffield for environmental performance validation
- Novel sensors & data processing
  - Automated defect and object recognition
  - Ultrasonic sensors
  - Contact sensors (whisking etc)

Centre for Ultrasonic Engineering