MONITORING SAFETY CRITICAL INFRASTRUCTURE WITH MOBILE ROBOTS

Plenary Keynote

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Abstract:

Reliable Non Destructive Testing (NDT) is vital to the integrity, performance management and sustainability of capital assets in safety critical industries such as oil and gas, aerospace, transportation, power generation and off-shore and subsea operations. The talk will highlight opportunities to improve the NDT of industrial structures and decrease the cost of inspection by automating the NDT with mobile robots. The challenge is to develop robots that can provide access to test sites and perform reliable NDT on very large vertical structures or structures located in hazardous environments thereby eliminating the large expense of erecting scaffolding or lengthy preparation for rope and platform access before inspection can start. The presentation will show climbing and swimming robots developed to detect weld and corrosion defects on ship hulls, floating platforms, mooring chains, petrochemical storage tanks, pressure vessels, concrete structures, wind blades and aircraft wings and fuselage. These developments provide the possibility of saving costs by reducing outage times or (where possible) carrying out the NDT in-service thus preventing expensive outages.

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Monitoring Safety Critical Infrastructure with Mobile Robots

Opportunities and Challenges

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TWI

London South Bank Innovation Centre

London South Bank University, School of Engineering

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London South Bank Innovation Centre for Automation of NDT based in Granta Park, Great Abington, Cambridge CB2 6AL

Keynote organisation

- **Introduction** → Application areas
- **Motivating examples** → Gas boiler, Ship hulls, Offshore structures, dams, nuclear structures
- **Robotic NDT** → The 4 M's → Mobility, manipulation, measurement, monitoring
- **Mobility & manipulation** → Wall climbing robots
- **Measurement** → Standard NDT techniques → Ultrasound, TOFD, Eddy Current, Thermography
- **NDT Robot prototypes** → Storage tanks – RobTank, TankRob, Nautilus → Nuclear plant – Pressure vessels, nodal pipes → Nuclear decommissionin g
- **Offshore underwater** → FPSO's → Mooring chains → Oil & gas flexible risers → Floating platforms → Wind turbines
- **Conclusion**

INTRODUCTION

Capital Assets in safety critical industries have the following characteristics:

1. Expensive assets require regular monitoring to
   - ensure their safe operation
   - acquire condition data to plan outages for maintenance
   - extend life of asset.
2. Large structures with test sites at remote locations
3. Located in extreme and hazardous environments
4. Inspection requires an outage with pressure to reduce turn-around time

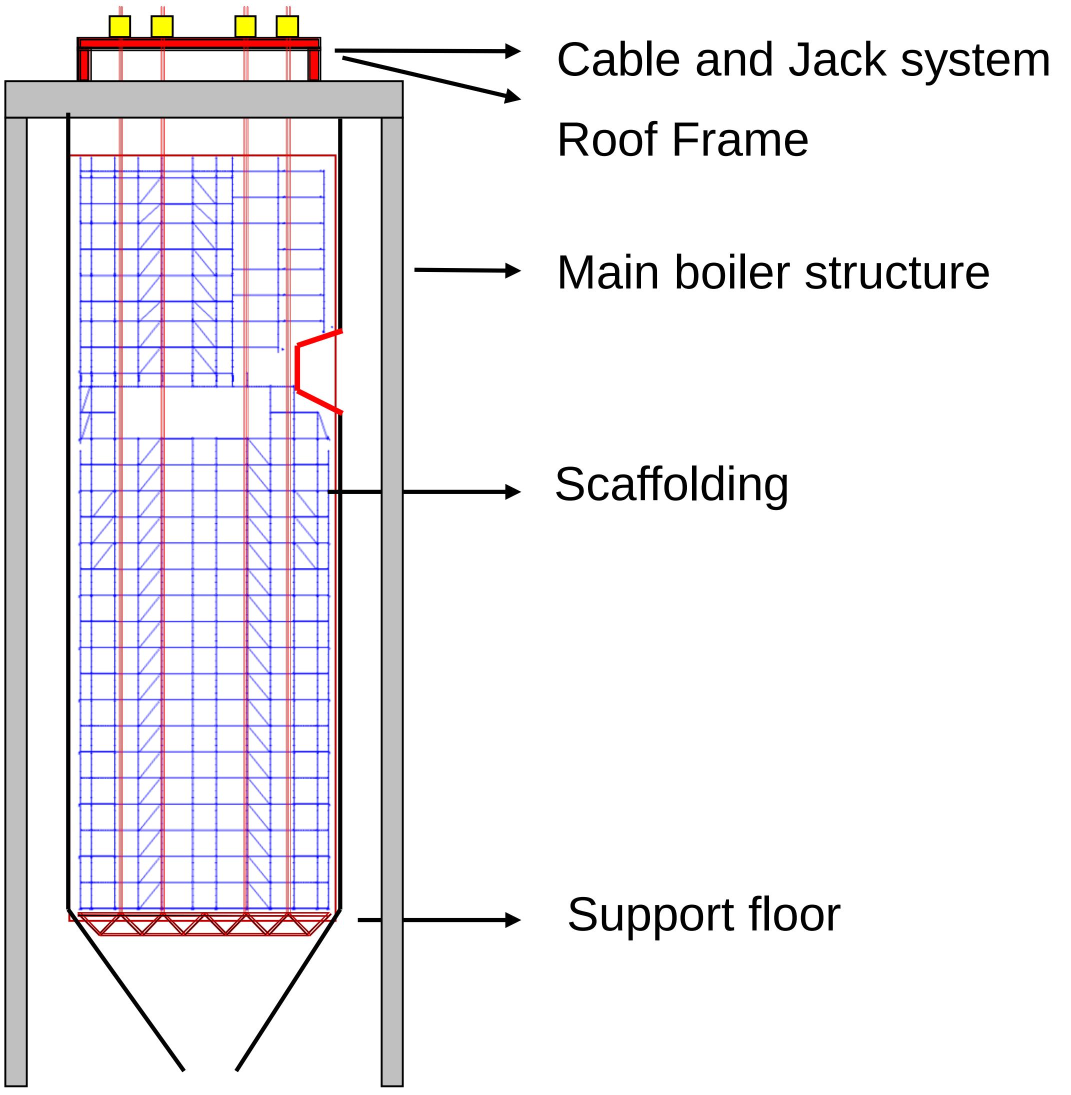
Oil and gas industries-
- **Petrochemical storage tanks**
- **FPSO's – Floating platform storage of oil**
- **Flexible risers**
- **Mooring chains and lines**
- **Oil and gas platforms**
- **Pipelines**

Nuclear power plants & decommissioning
- Nozzle welds on pressure vessels and in primary circuit
- Radiation reprocessing cells
- Aerial stacks
- Concrete buildings

Renewable energy –
- Wind turbine towers and blades
- Tidal generator blades
- Off-shore monopiles for WTG's
- Dam walls in air and underwater

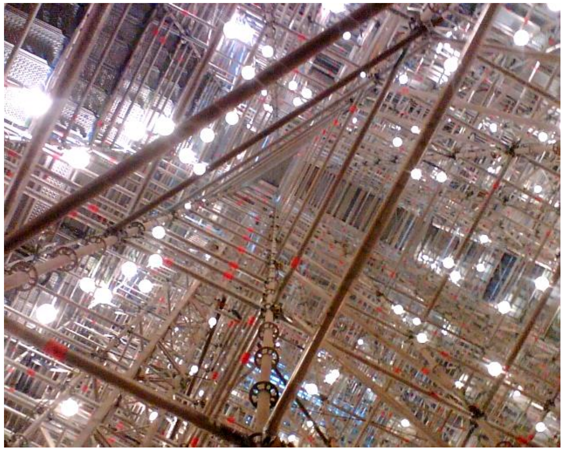
Transportation -
- Railway lines - cracks
- Aircraft - rivets, composite impact damage
- Ships – welds and corrosion

Inspection of 90 m tall gas boiler



Five recent deaths due to scaffold collapse

Portaalframe strand Jack system



Internal inspection of gas boiler using suspended platforms

Outage in Coal Power Plants

MAJOR OUTAGE **Every 8 -10 years**	• **200 MW unit, 16 weeks** • **110 MW unit, 12 weeks**
OUTAGE Every second year	• 200 MW unit, 3 weeks • 110 MW unit, 2 - 3 weeks

Opportunity to reduce turn-around time with robotics and automation

Robotic Non Destructive Testing (NDT)

Ultrasound NDT of horizontal and vertical welds on a new build cargo container ship – Odense Shipyard

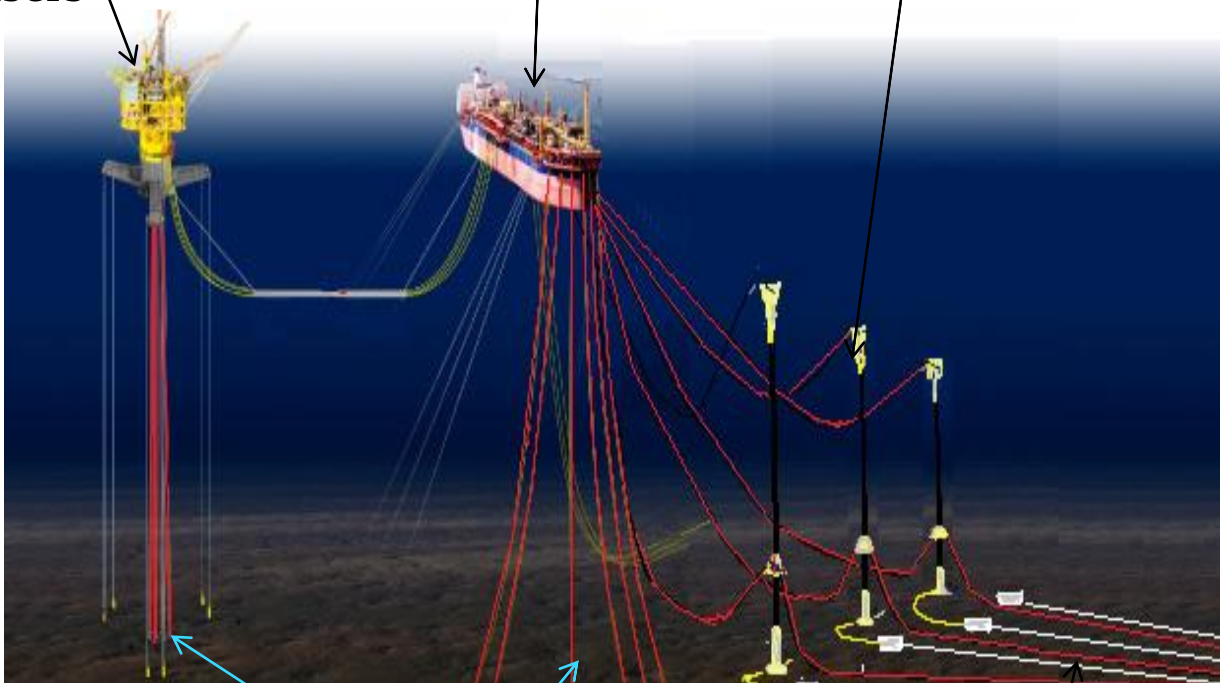
Dimensions:

30m height

30m width

300m length

The floating platform, mooring chain, oil & gas flexible riser, flow-line, tie-back and tidal generator environment



DAM FAILURES

2005-2009 - 132 dam failures in the US with $54.3M in repair and downstream costs. Reported diver deaths in 2014

Dam	Type	Country	Height m	Res Vol ($10^6 m^3$	Built	Failure		Deaths
						Date	Type	
Vega de Tera	CMB	Spain	34	7.8	1957	1959	SF	144
Malpasset	CA	France	66	22	1954	1959	FF	421
Babii Yar	Emb	Ukraine				1961	OF	145
Vaiont	CA	Italy	265	150	1960	1963	L	2,600
Baldwin Hills	Emb	USA	71	1.1	1951	1963	IE	5
Frias	Emb	Argentina	15	0.2	1940	1970	OF	42+
Banqiao	Emb	China	118	492	1953	1975	OF	#
Teton	Emb	USA	93	308	1975	1976	IE	11
Machhu II	Emb	India	26	100	1972	1979	OF	2,000
Bagauda	Emb	Nigeria	20	0.7	1970	1988	OF	50
Belci	Emb	Romania	18	13	1962	1991	OF	25
Gouhou	Emb	China	71	3	1989	1993	IE	400
Zeizoun	Emb	Syria	42	71	1996	2002	OF	20
Camara	RCC	Brazil	50	27	2002	2004		5
Shakidor	Emb	Pakistan			2003	2005	OF	135+
Situ Gintung	Emb	Indonesia	16	2		2009	IE	100

Dam type: CA = concrete arch, CMB = concrete and masonry buttress, Emb = embankment, RCC = roller compacted concrete.
Type of failure: IE = internal erosion, FF = foundation failure, OF = overtopping during flood, SF = structural failure on first filling, L = 270 x 10^6 m^3 landslide into the reservoir caused overtopping of the dam by a wave 125 m high, but remarkably the dam survived.

National and regional legislations (e.g. Reservoirs Act 1975 - UK1; Technical Regulation on Dams and Reservoirs 1996 - Spain2; Association of State Dam Safety Officials Program Policies and Standards - USA3; Water Law of the People's Republic of China 19884)

Robotic Non Destructive Testing (NDT)

R&D of Mobile robots to provide access and perform NDT of

- very large structures
- test sites located in dangerous and hazardous environments

The aim is to

- reduce inspection costs, outage times during planned outages
- Provide in-service inspection where possible to eliminate outages

The 4 M’s of Robotic Non-Destructive Testing	
Provide access to a test site with mobile robots	MOBILITY
Deploy NDT probes	MANIPULATION
Acquire data to detect and size defects	MEASUREMENT
Store and use data to monitor state of infrastructure	MONITORING

Mobility
Manipulation

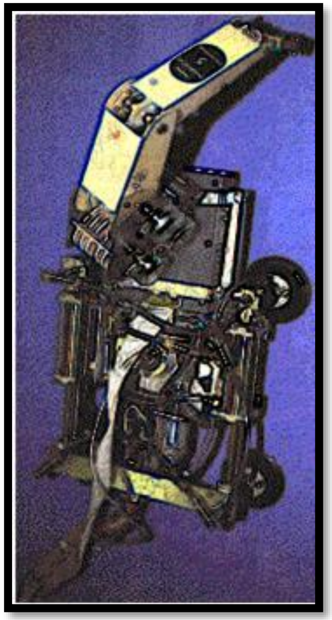
Provide access to remote test site located in extreme environments

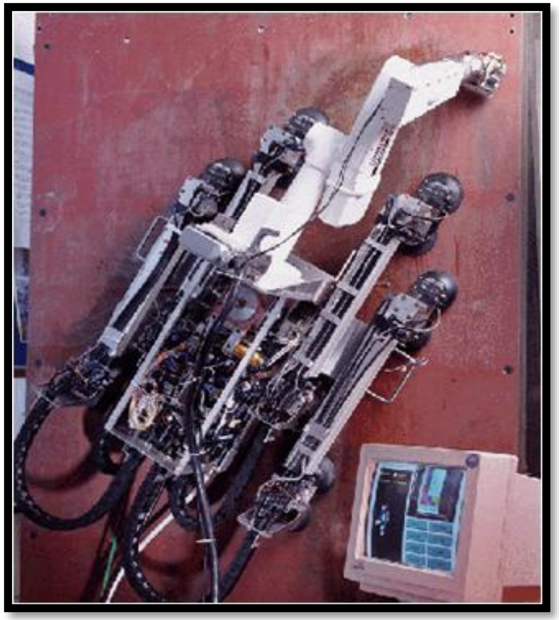
Wall climbing robots that use pneumatic suction cups

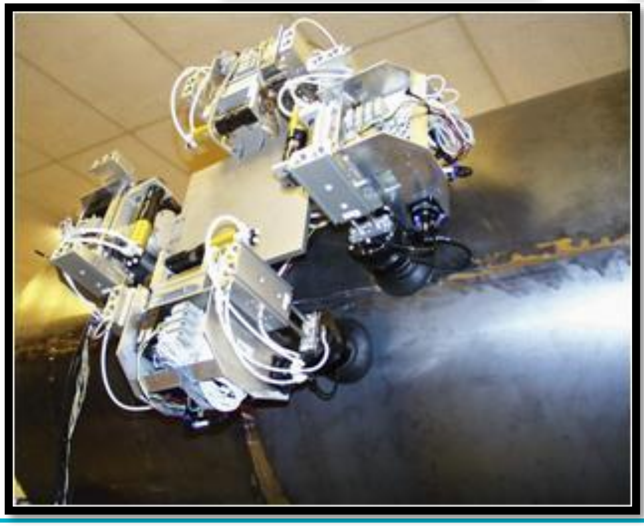
Worlds First

wall climber

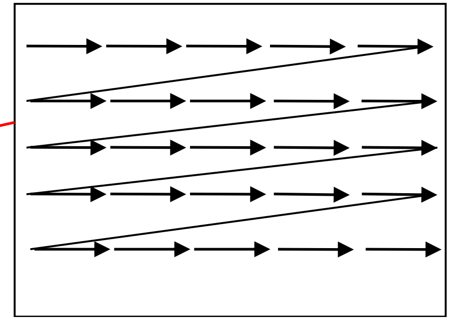
1992



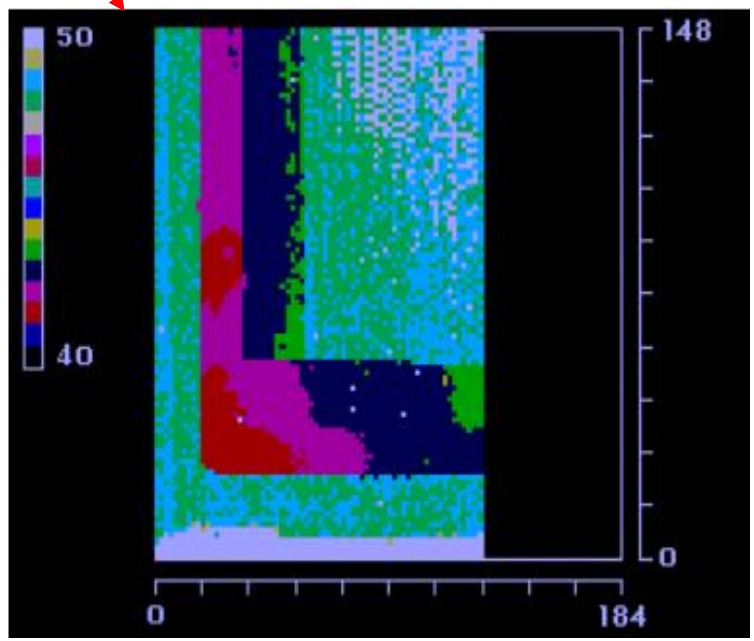




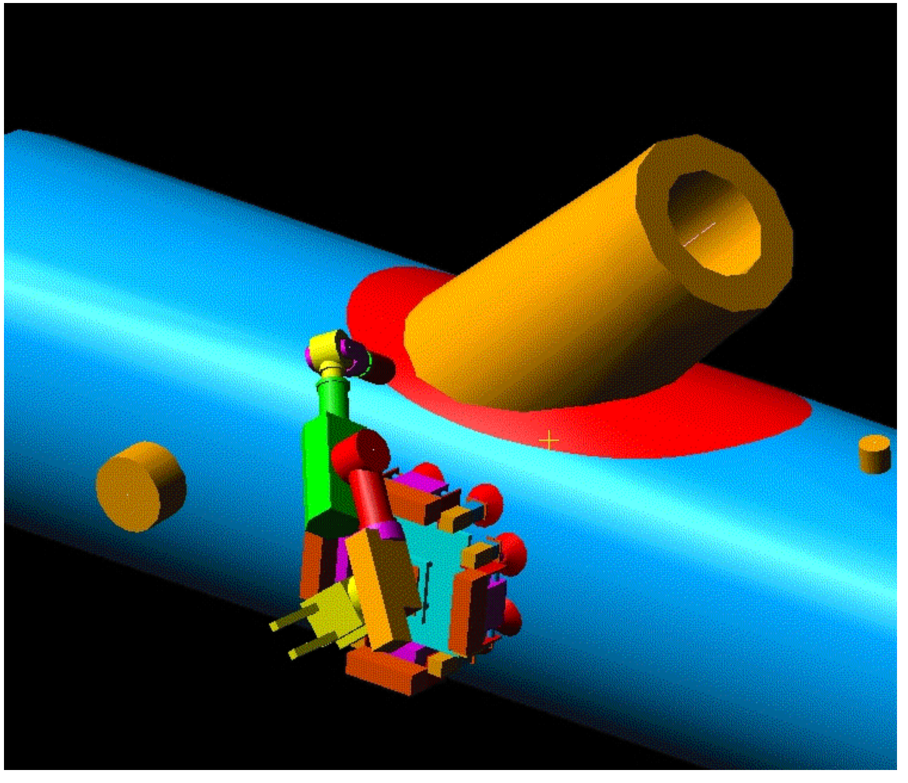
SBU

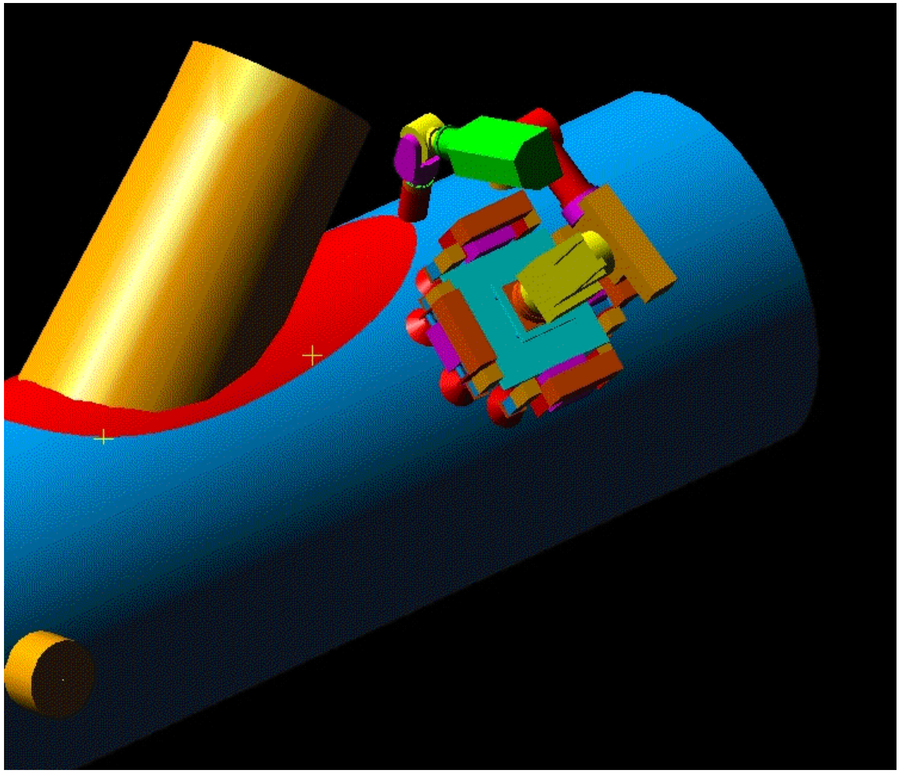


Raster-scan with UT probe

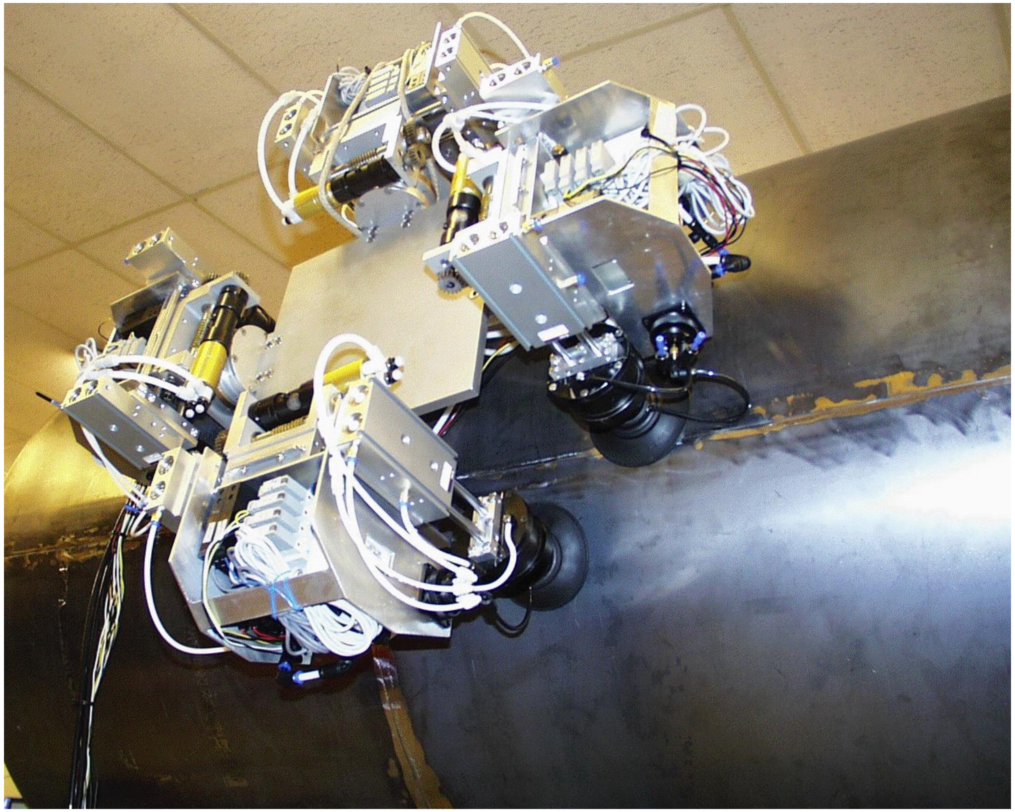


C-scan image of corrosion thinning (variable thickness 0 - 6 mm measured from the back wall) of a 10mm thick steel plate, adjacent colors corresponding to thickness steps of 0.375 mm. Data obtained with 5 MHz wet contact compression wave probe (8mm diameter)





CAD schematic drawing - mobile inspection robot deploying NDT sensors with 7-axis arm.



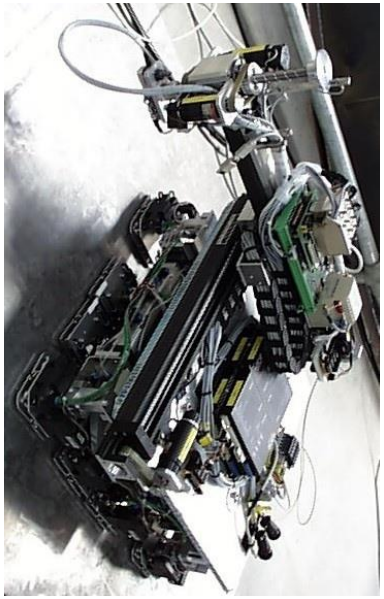
Prototype generic vehicle - 4 thigh joints for motion on spheres -conventional suction cups -payload 6 kg with a safety factor of 3

Ultrasound NDT of nozzle welds in primary circuit of nuclear power plant

Pipe diameter 860 mm, vehicle mass = 30kg, 500x500 mm, max P= 37 kg, arm mass = 22 kg, 7 DOF, arm payload = 5 kg, repeatability ±1 mm, couplant retrieval system, force controller

Climbing NDT robots that use different adhesion techniques: permanent magnets, pneumatic suction cups and Vortex machines

CROCELLS



ROBAIR

VORTEX

Wall climbing robots for the NDTof welds on cargo containers ships

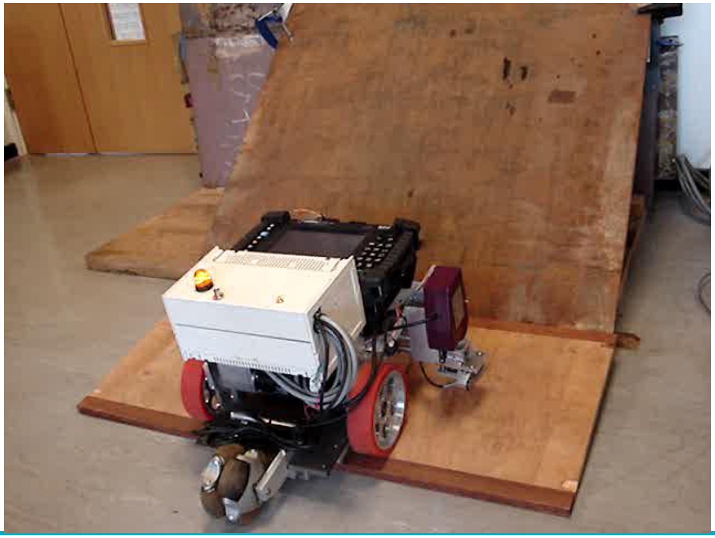
Permanent magnets

Wireless control and data acquisition

Ultrasonic phased array NDT

Laser weld profiling and tracking

Mass 35Kg



InnovateUK funded project AWI (Autonomous Weld Inspector) is currently developing a more advanced version of this robot

Climbing Robot Cell for welding and NDT - CROCELLS

- Team of climbing robots
- One performs Electric arc welding by profiling seam with a laser system
- A utility robot follows the welder and carries the wire drum and feeder
- A tug robot aides the welding robot
- An NDT robot tracks the welding hot spot and performs weld inspection with phased array ultrasonics

Magnetic adhesion climbing robots

Adapt to surface curvatures (concave or convex) or change surfaces

NDT robot adapts to Convex/Concave structures

WALLEXPLOR

Wall climbing robots for NDT, inspection and surveillance on non-ferrous surfaces

ANSYS analysis of streamlines and pressures created by VORTEX machines

Aim: Increase Payload capability of climbing robot

Achieved: 4 kg with an A4 sized robot.

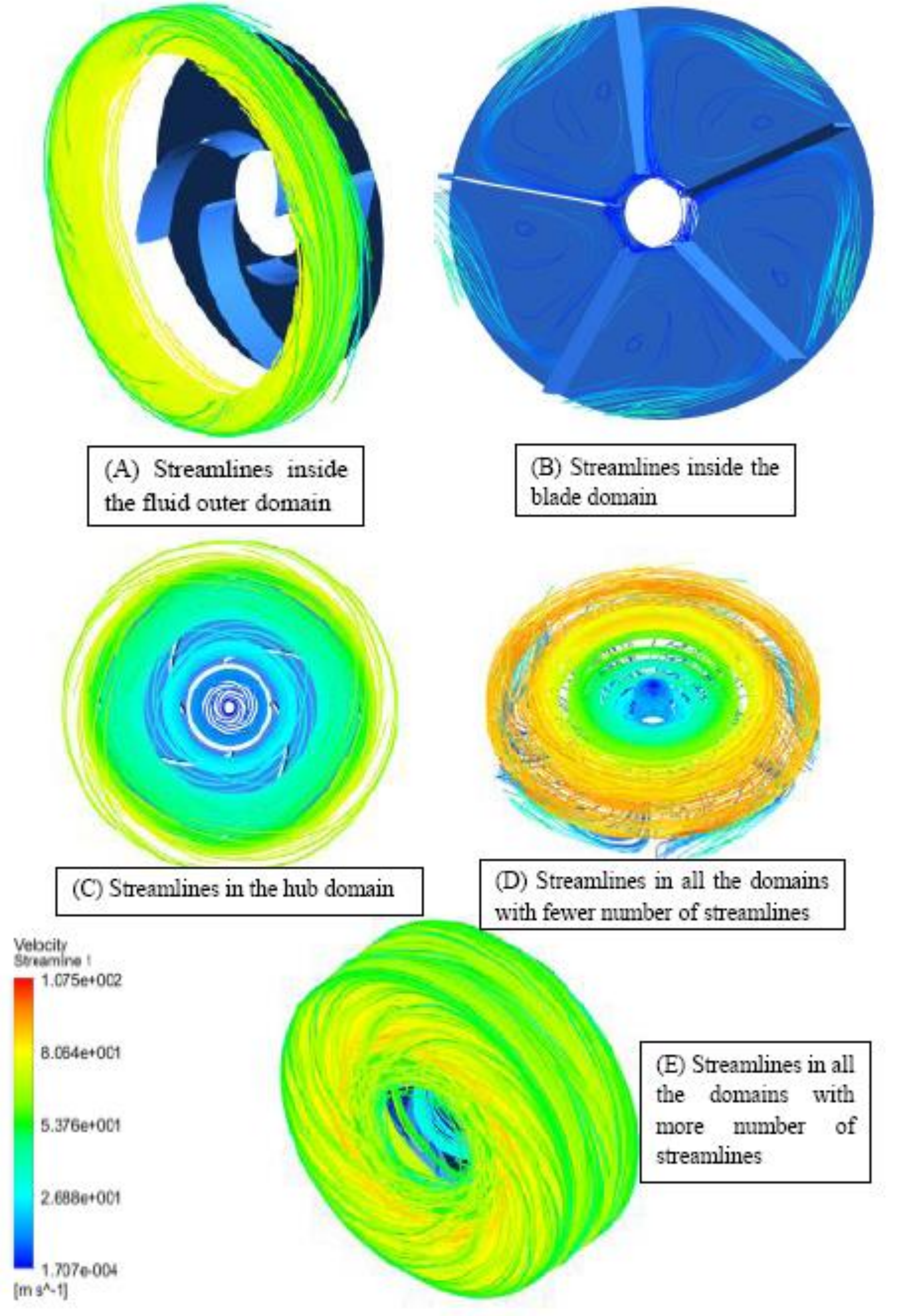
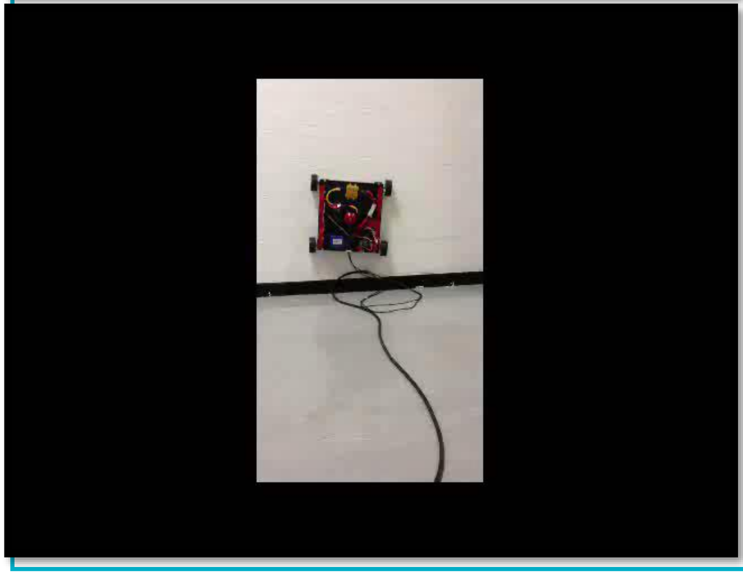
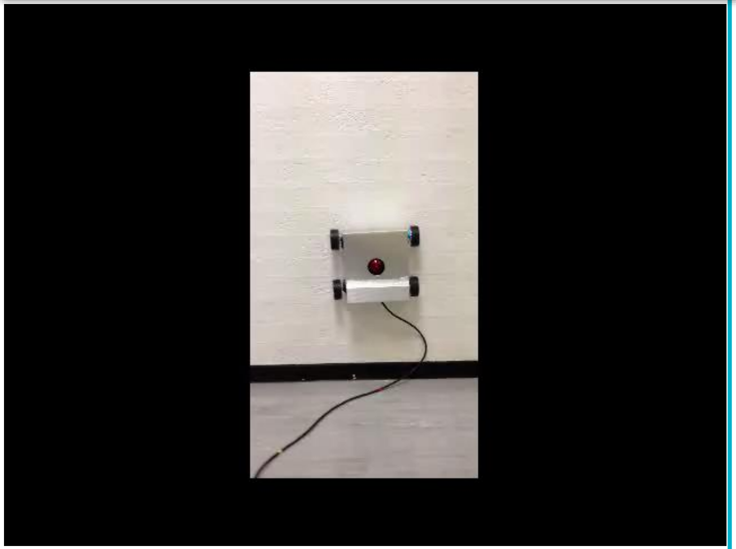


Figure 3-10 isometric view to show the streamlines inside the vortex chamber in the blades

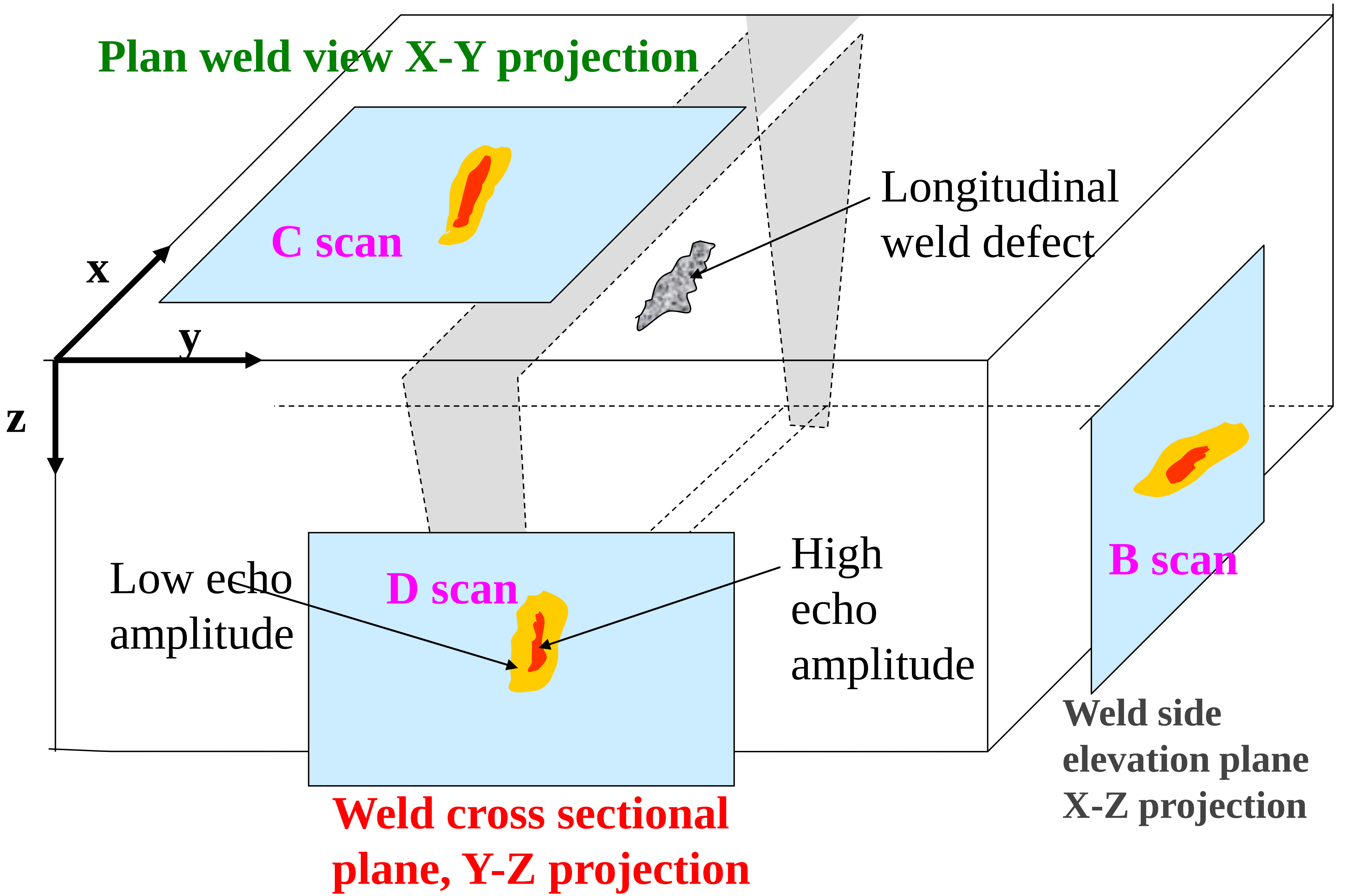
VORTEX MACHINES: Wall climbing robots for NDT, inspection and surveillance on non-ferrous surfaces





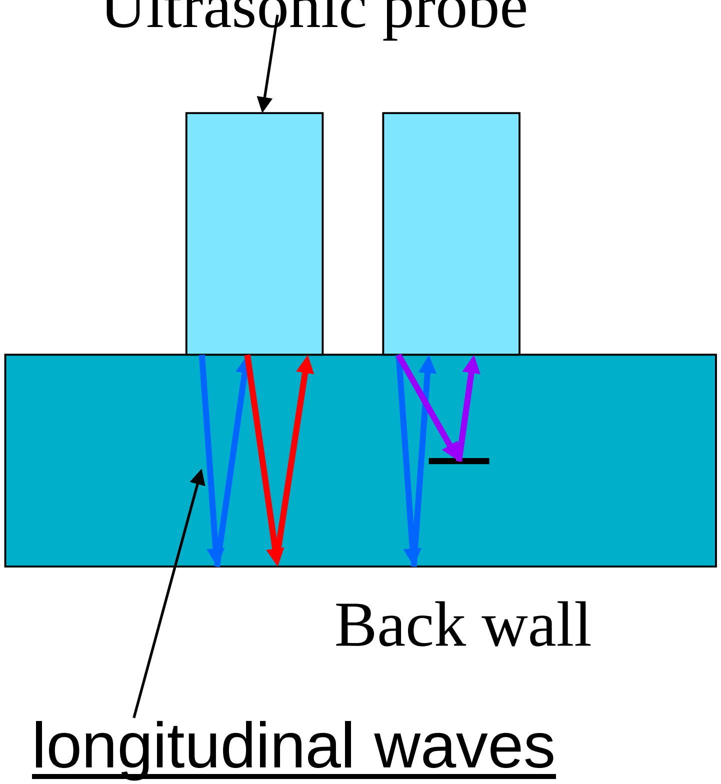
Measurement

Non-destructive testing (NDT) techniques

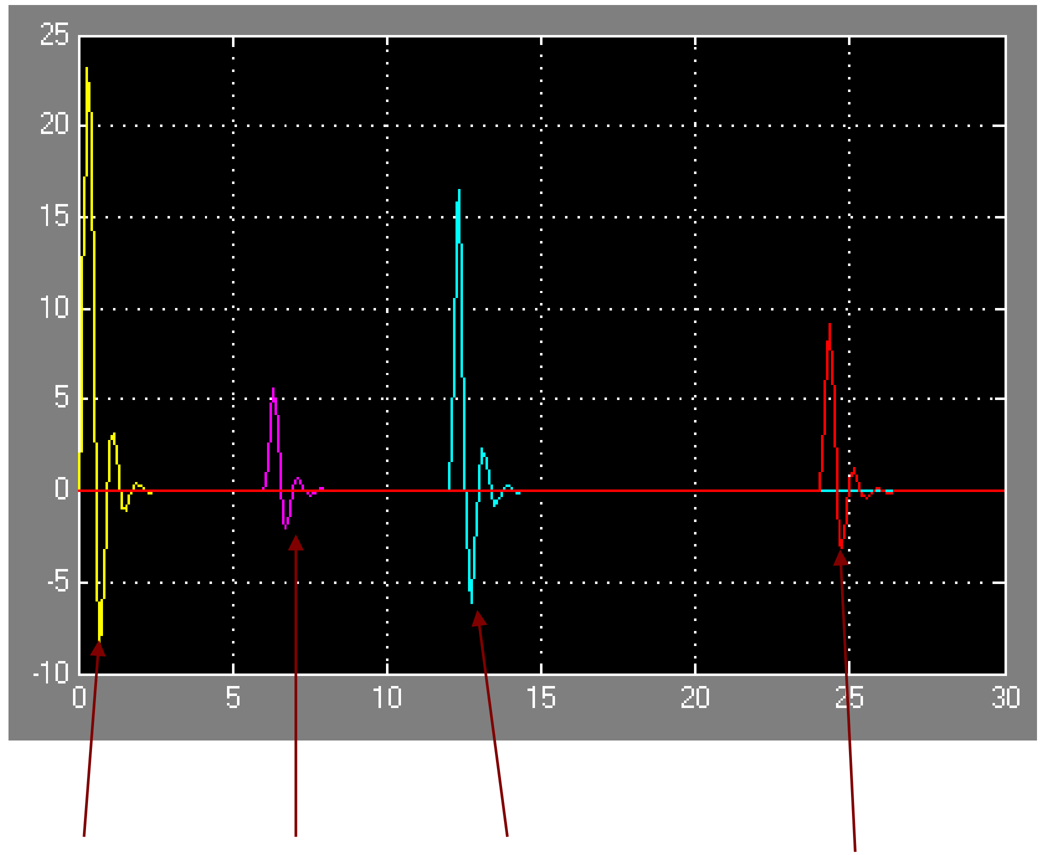


Display of weld defect on orthogonal planes related to the weld.

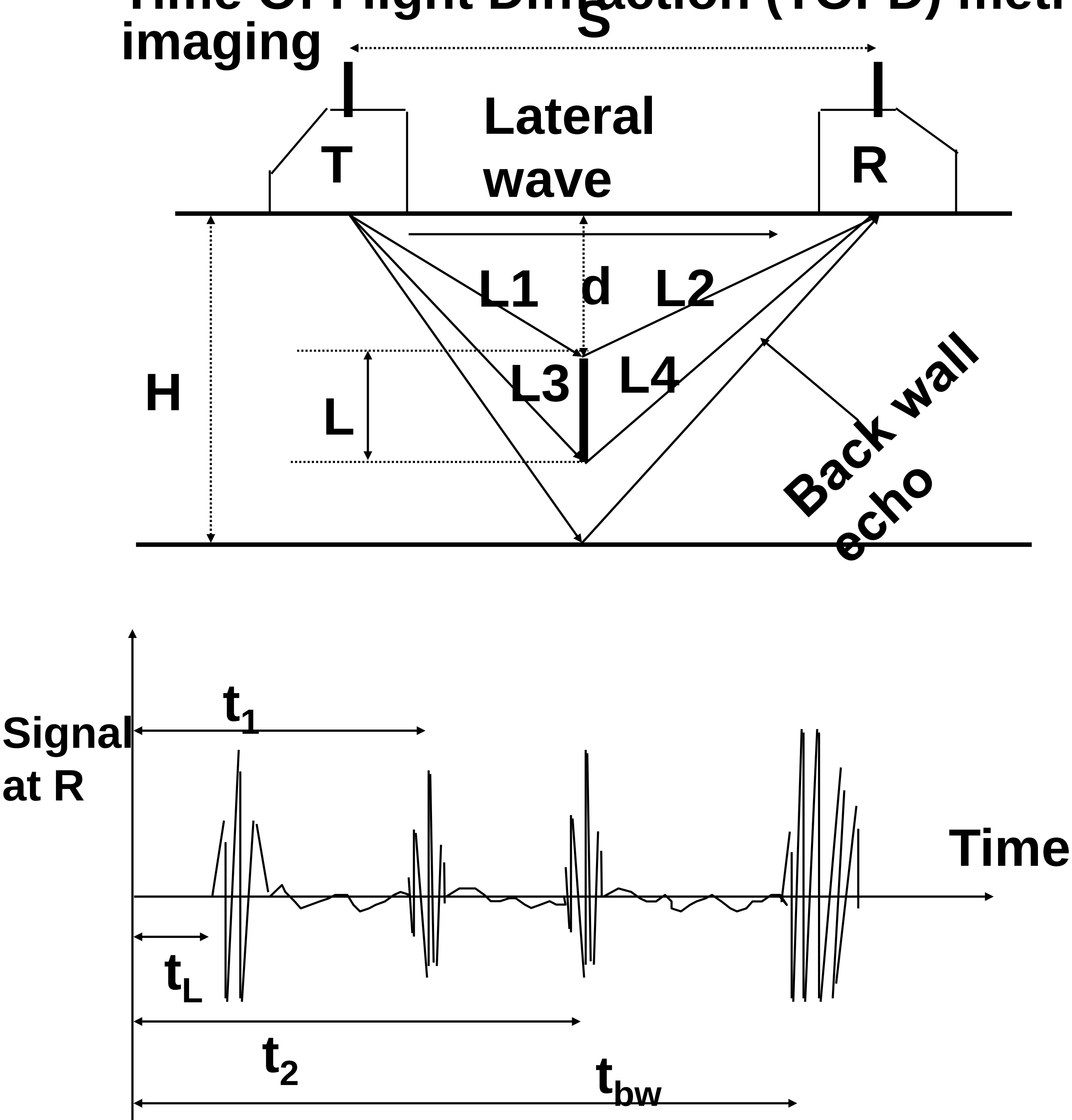
0° compression wave



A-Scan



Time Of Flight Diffraction (TOFD) method B-Scan imaging



T – Transmitter

R – Reciever

H - Plate thickness

L - Size of the defect

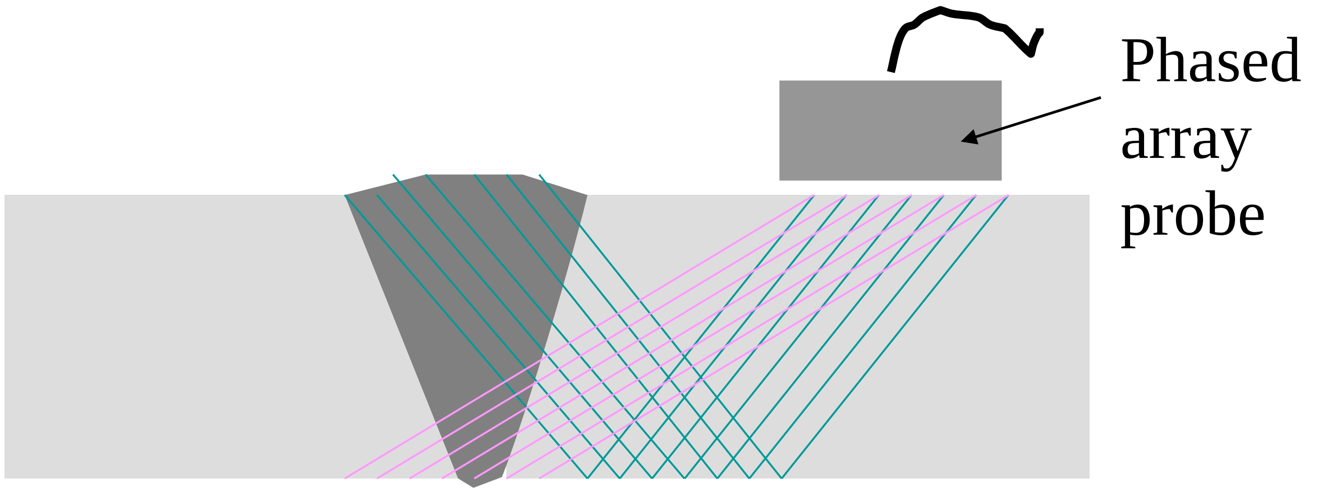
t_L - Time for the lateral wave

t_1 - Time for the top tip diffraction along the path (L1+L2)

t_2 - Time for the bottom tip diffraction along the path (L3+L4)

t_{bw} - Time for the back wall echo

Phased array ultrasonics

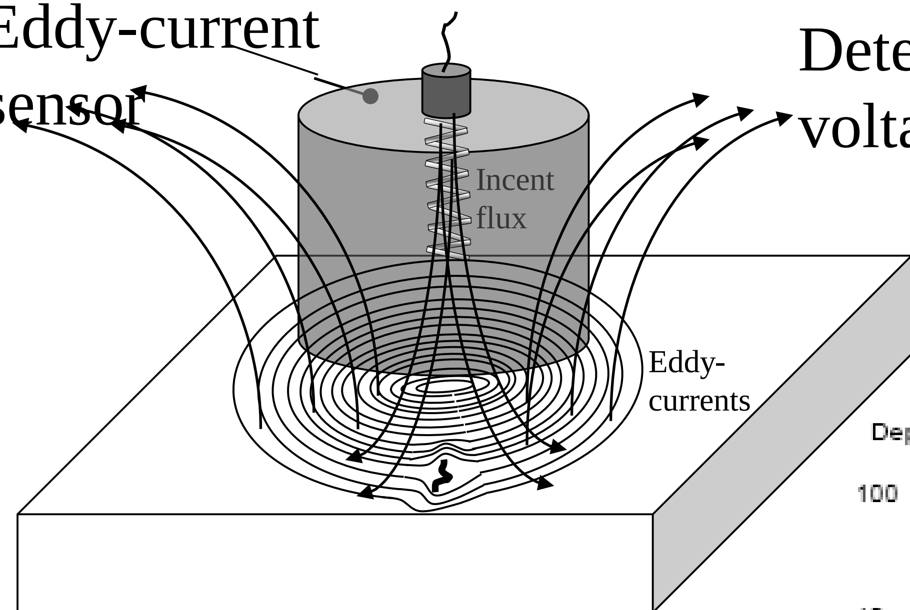


• Array of elements, all individually wired, pulsed and time shifted.

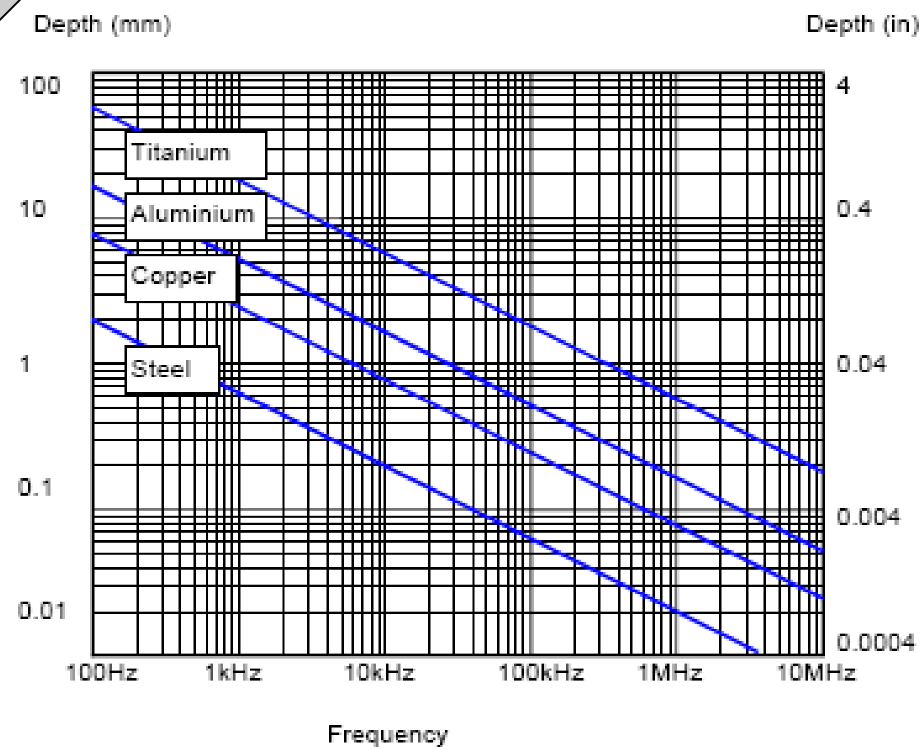
• Each element generates a beam when pulsed; these beams constructively and destructively interfere to form a wavefront.

• Electronic beam steering reduces the number of scanning axes required to examine a defect

EDDY-CURRENT INSPECTION



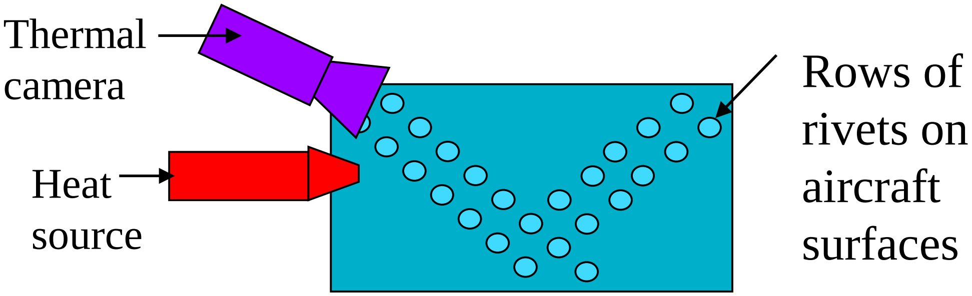
Detection of change in voltage by second coil

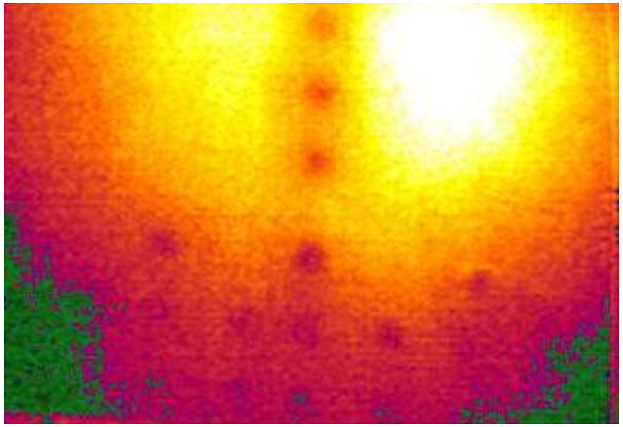


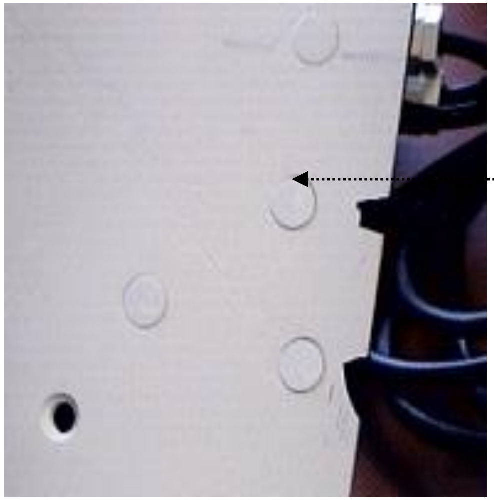
Method suitable for near surface inspection

Lower frequencies give greater depth detection

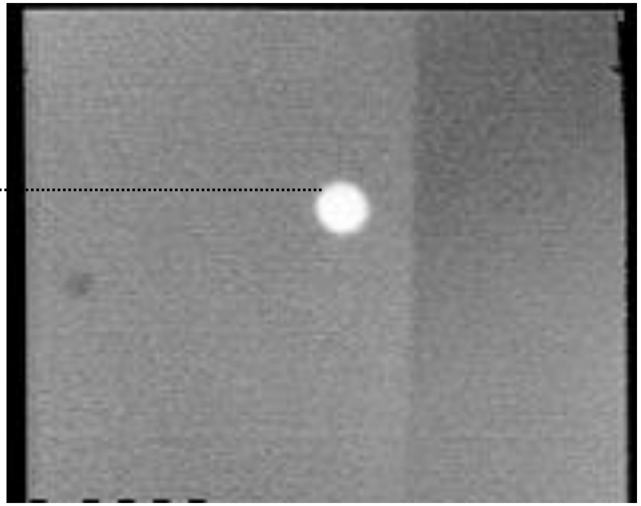
Thermographic NDT





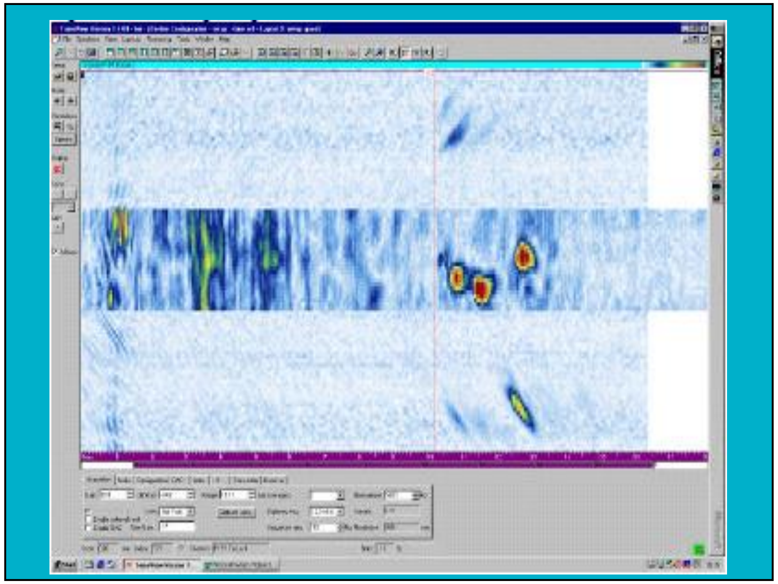


Loose rivet on an aircraft wing

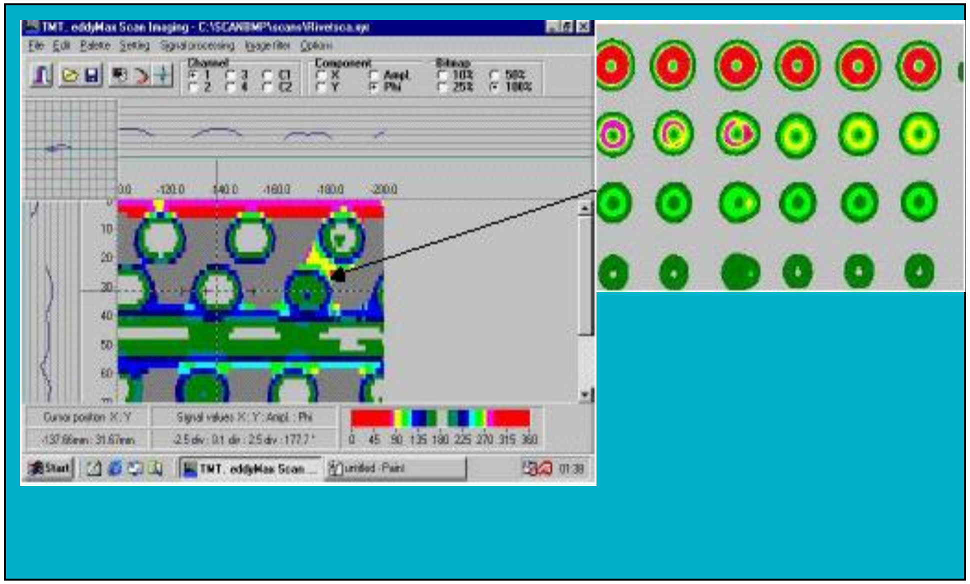


Thermal image of loose rivet

Examples: imaging of rivet defects with Ultrasound Phased Arrays, Eddy Currents



ULTRASONIC PHASED ARRAY to inspect rivets on aircraft, ROBAIR project



EDDY CURRENT inspection of rows of rivets on the wings and fuselage of aircraft, ROBAIR project – detects slot between two rivets

- Petrochemical storage tanks
- Nuclear pressure vessels and pipes
- Nuclear decommissioning –radiation cells, aerial stacks, buildings
- Off-shore structures – Mooring chains, oil and gas flexible risers, FPSO’s

NDT ROBOT PROTOTYPES FOR INDUSTRIAL INSPECTION TASKS

STORAGE TANK INSPECTION

In-service inspection of petro-chemical storage tanks with mobile robots – RobTank project

Worldwide, over 218,000 petrochemical storage tanks and 53,000 large storage tanks with diameter > 50m are mostly inspected with outages. A large 100m diameter crude oil tank can be out of service for up to 9 months

Existing tank floor inspection activities

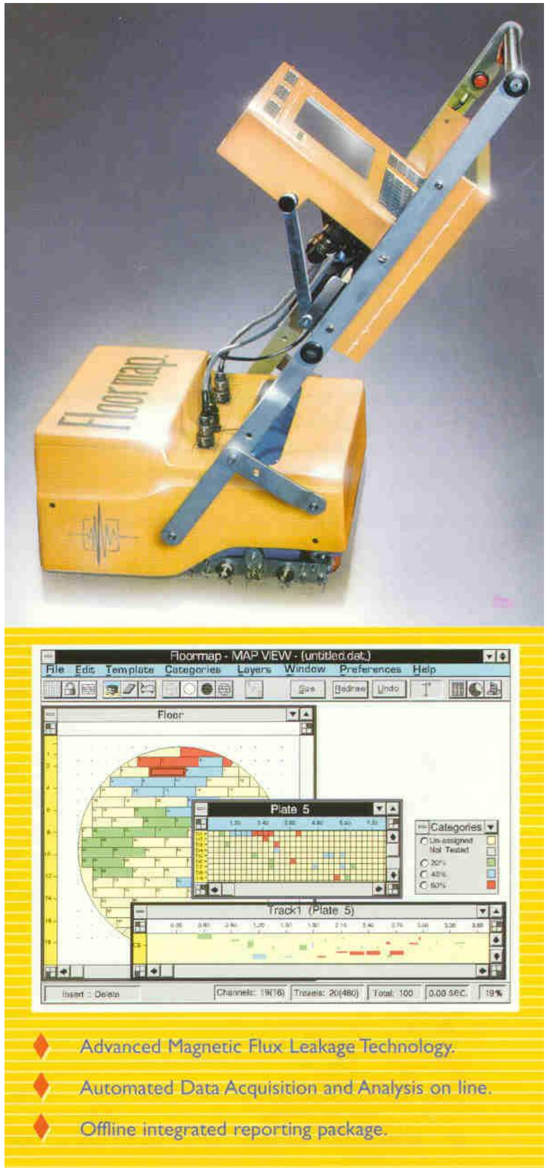
Preparing recipient tank
Moving contents to the recipient tank
Opening the tank under inspection
De-gassing the tank
Cleaning the tank – Sludge removal
Manual Inspection conducted by personnel
Closing the tank after inspection
Refilling the tank
Checking seals, vents, hoses etc.
Average Total Cost €90000

80% of cost is opening and closing the tank

CLEAN TANKS
Diameter 2 to 20 metres, fixed roof. Visual inspection, a few ultrasonic thickness measurements.

Crude oil tanks floating roofs, dia 20 - 100 metres, carbon steel. Floor thickness of 6-12.5mm, Preparation: 6-9 months .Another 3-6 months to clean .

Visual inspection followed by MFL. UT final method to validate the problem areas.

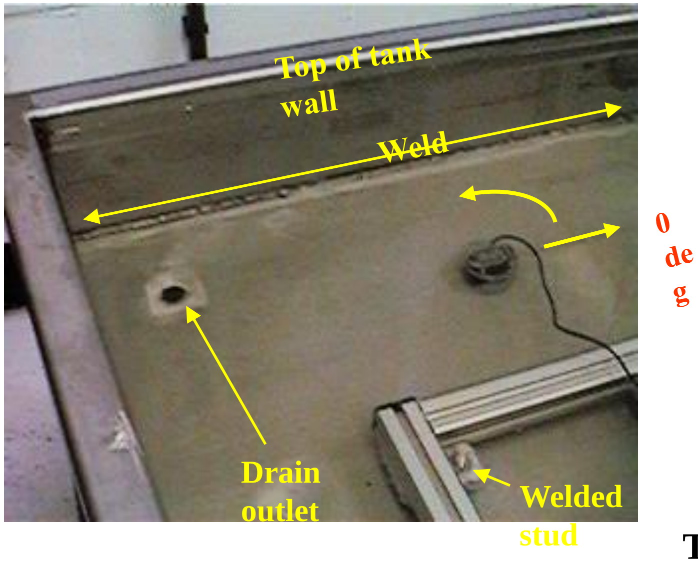


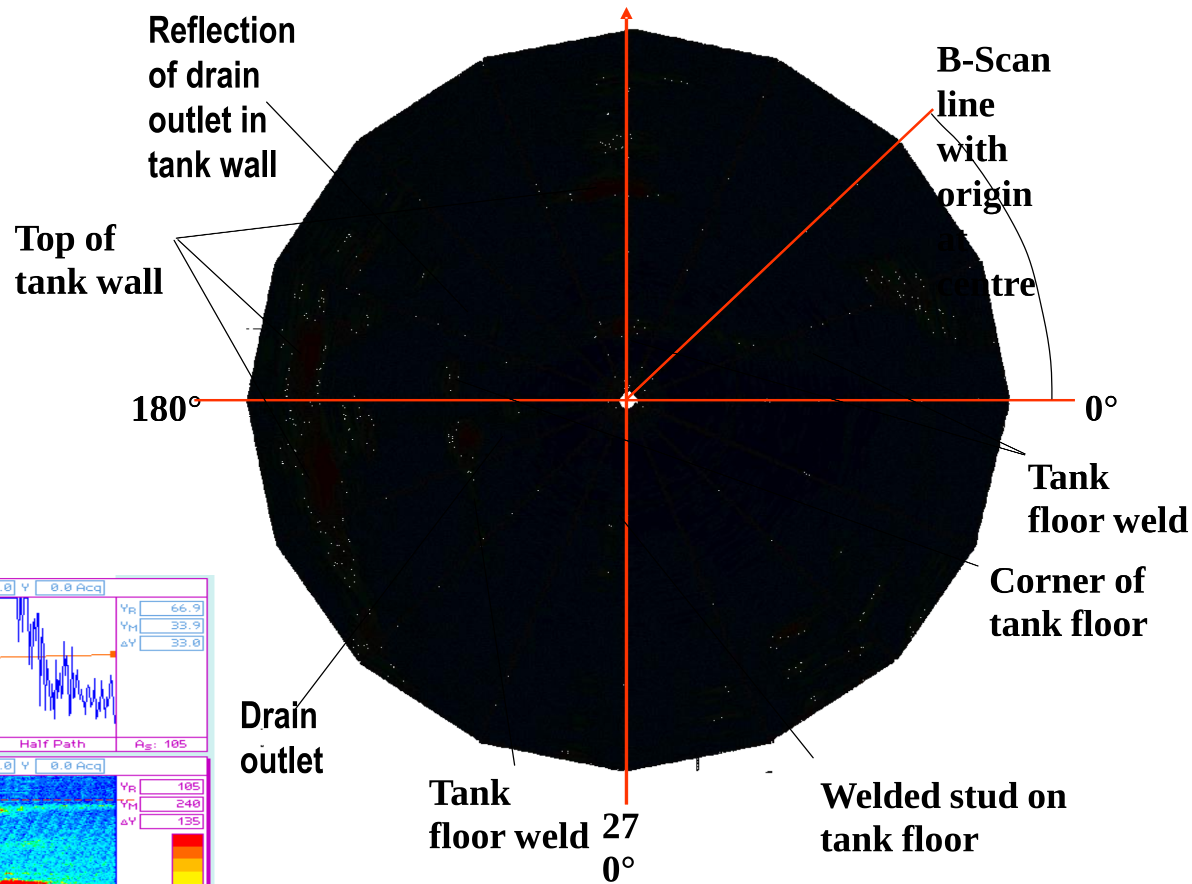
Manual tank floor inspection, underside corrosion defects

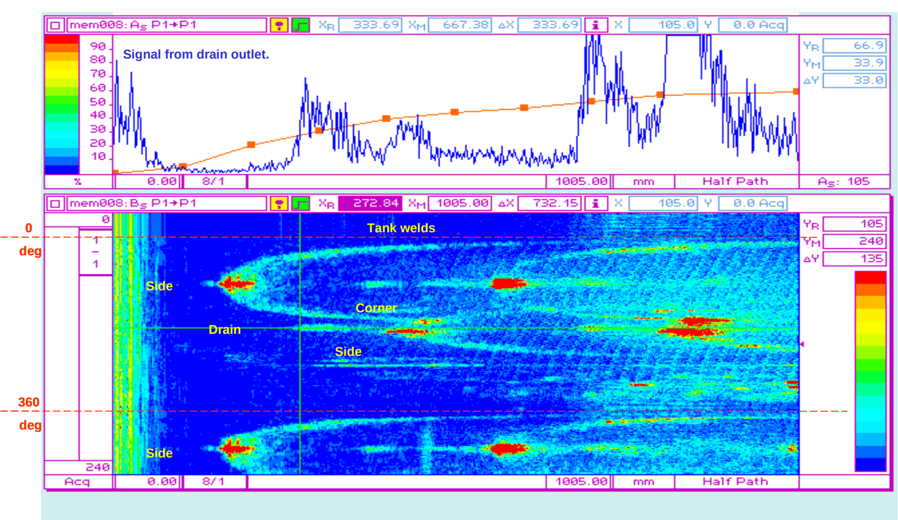
EU FP5 ROBTANK: Mobile wall climbing robot enters through manholes on the floating or fixed roof of a tank to inspect tank floor and internal walls

H2020 FTI TANKROB: Mobile robot to NDT tank floors with Phased Array Ultrasound – ATEX certification for Zone 1 operation

Mapping of floor defects using rotating bulk wave ultrasonic technique







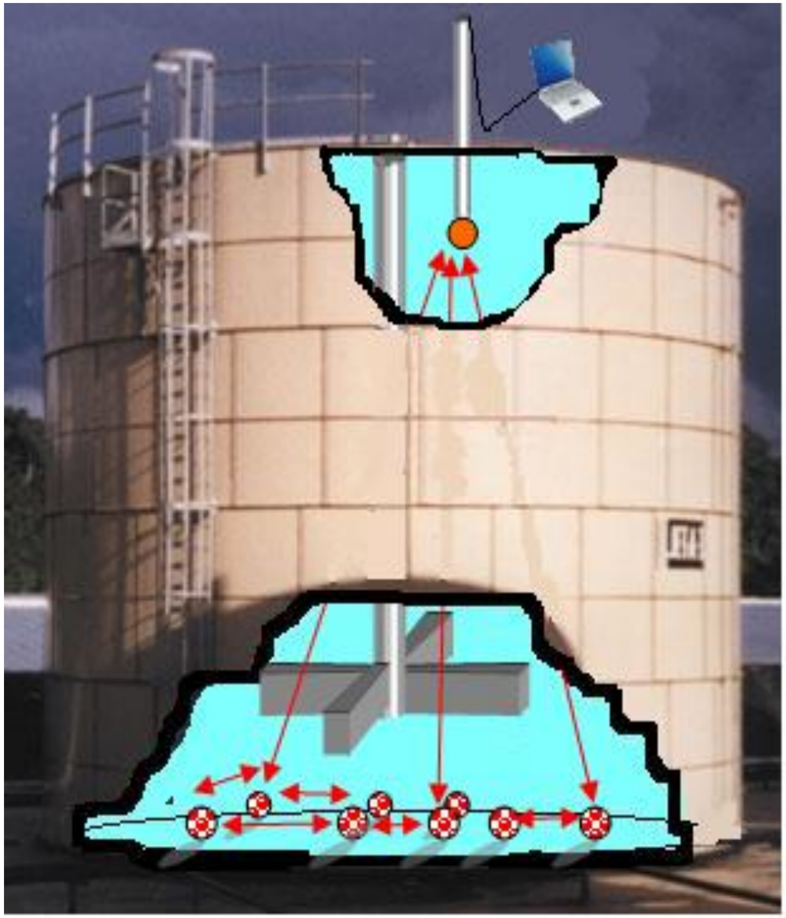
New InnovateUK funded project NAUTILUS: Bathyscaphic Robotic Floor Thickness Monitoring of Hazardous Liquid Storage Tanks

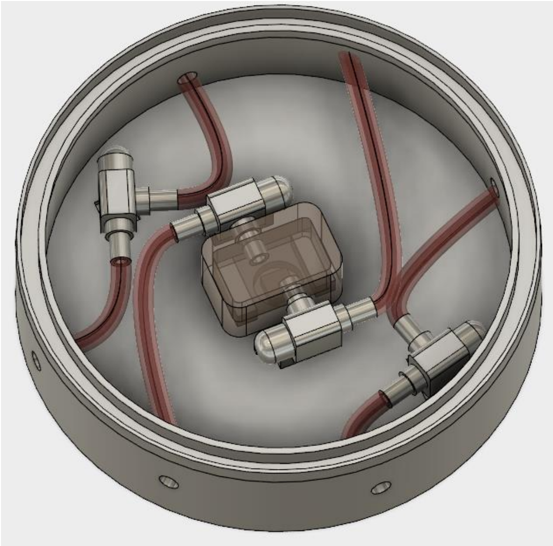
1. Active buoyancy control

2. Ultrasound NDT

3. Under liquid data communications

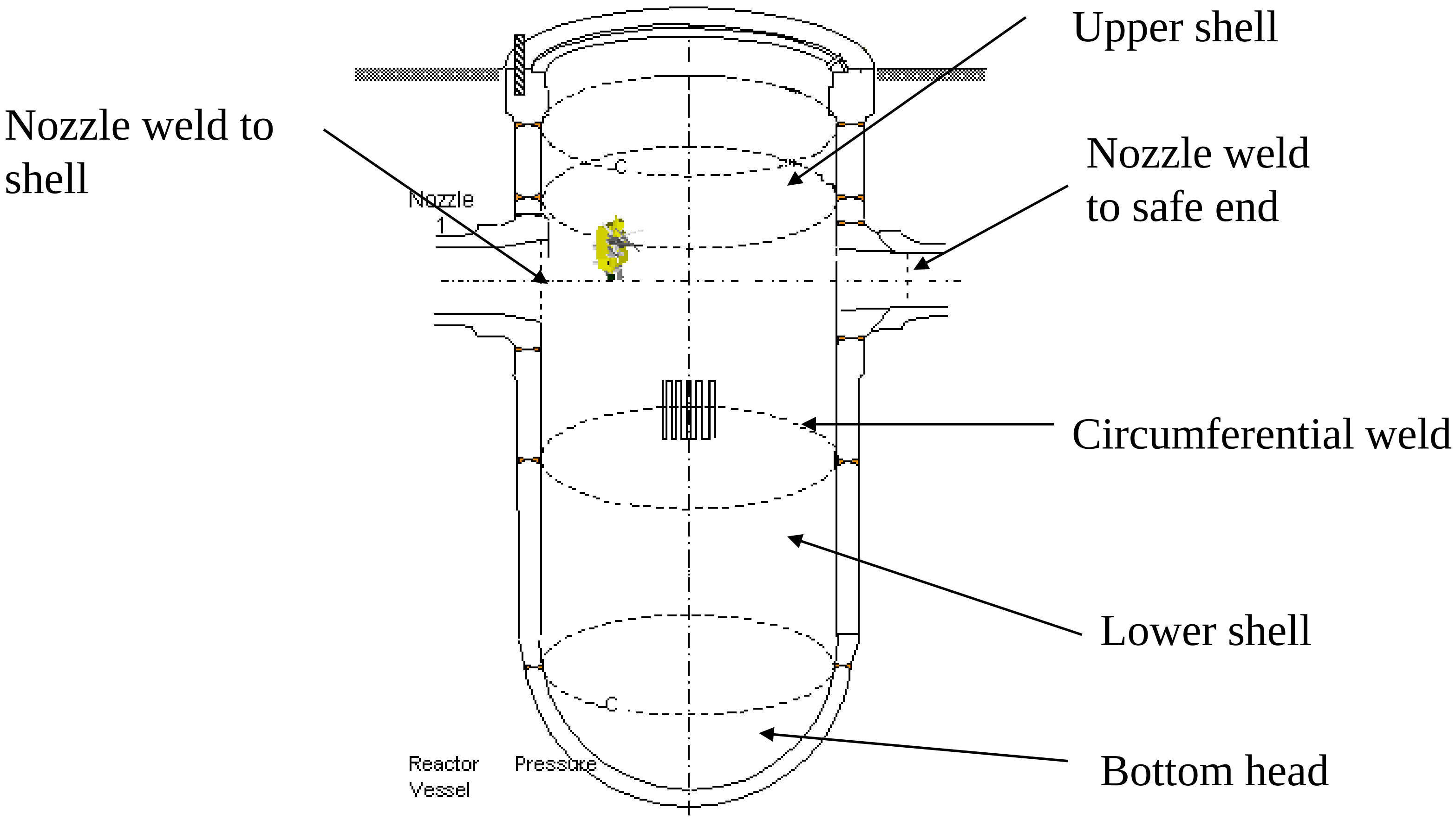
4. Zone 0 certification





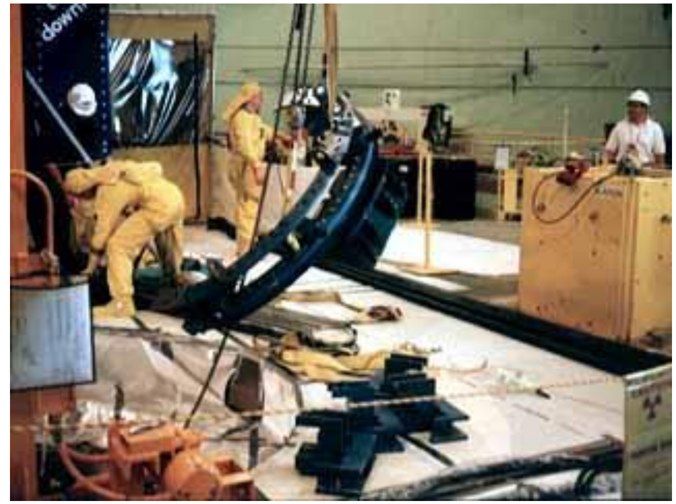
Nuclear power plant

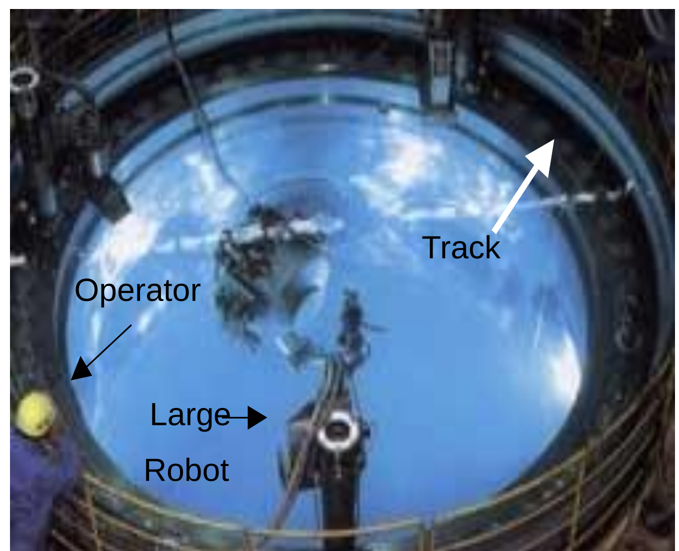
- RPV Circumferential and Nozzle welds
- Nuclear decommissioning



Current method of inspection uses large robots to do inspection – robot transported and assembled on site before immersion in RPV

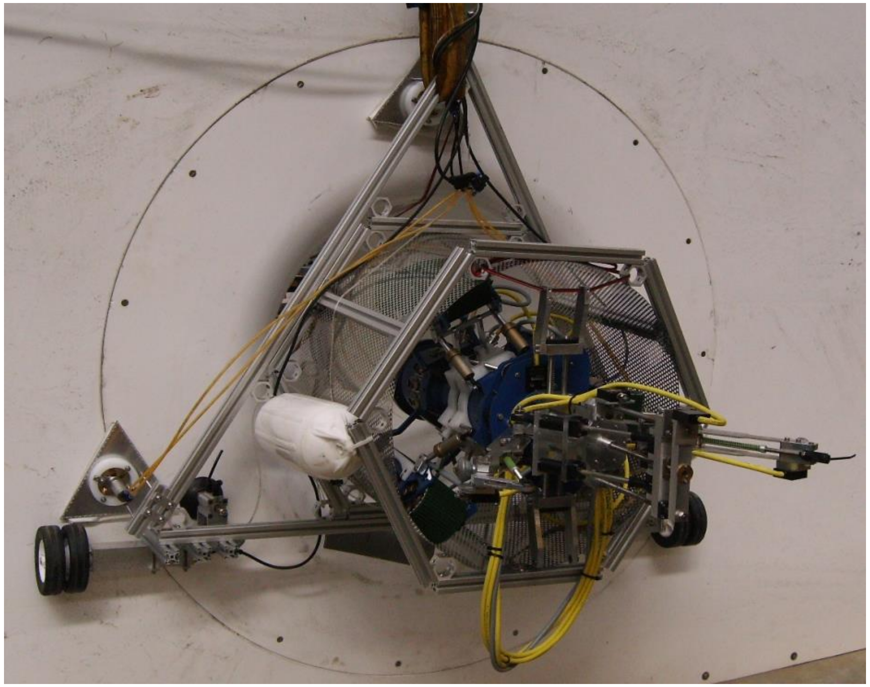
• Require large and heavy robots with a central mast costing millions, manual set up time, tying up of polar crane needed for other tasks

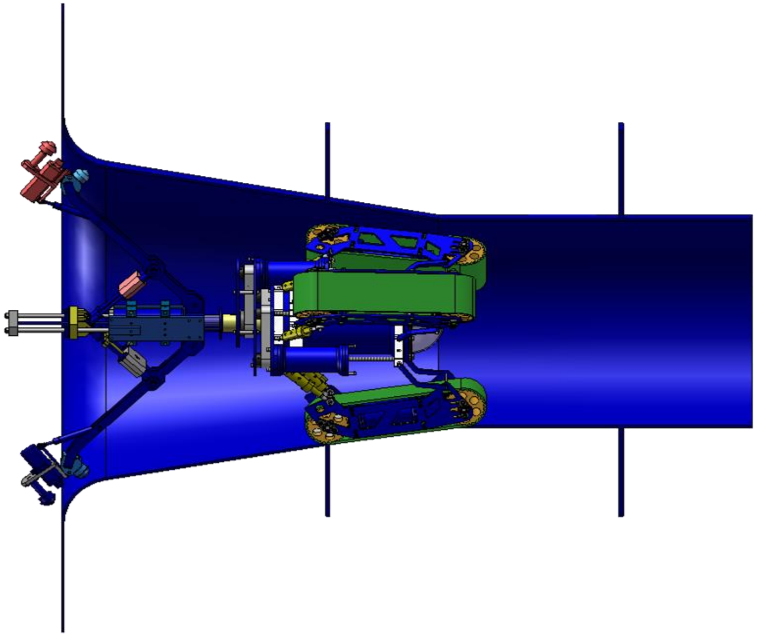


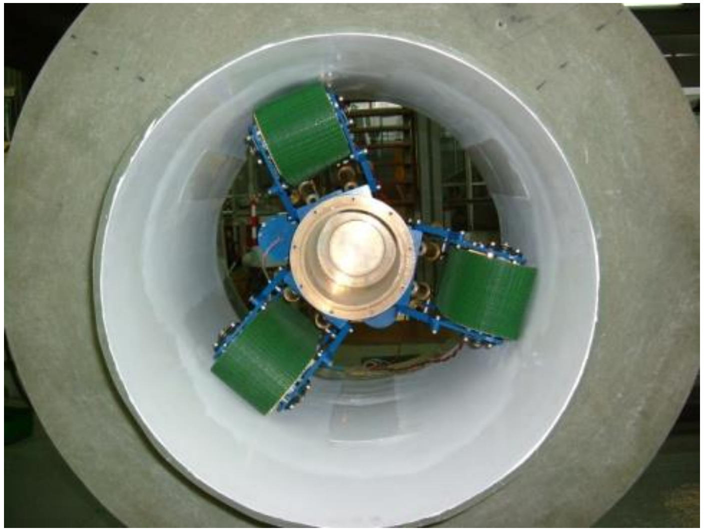


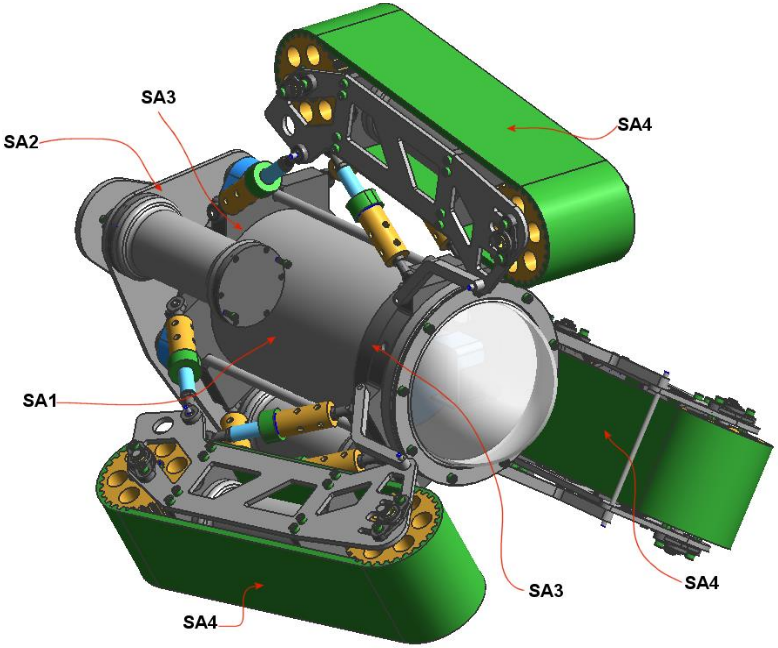
FP6-SME: RIMINI Development of new and novel low cost robot inspection methods for in-service inspection of nuclear installation

- Wall climber with nozzle crawler and scanning arm
- Neutrally buoyant climber+ nozzle crawler
- Positively buoyant climber, parked with suction cups





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Decommissioning of the Sellafield nuclear reprocessing site

- 120 concrete buildings housing reprocessing cells, nuclear waste
- £80 billion to be spent in next 5 years to decommission
- 120 years to decommission site

Inspection (1) – Large Structures and Buildings

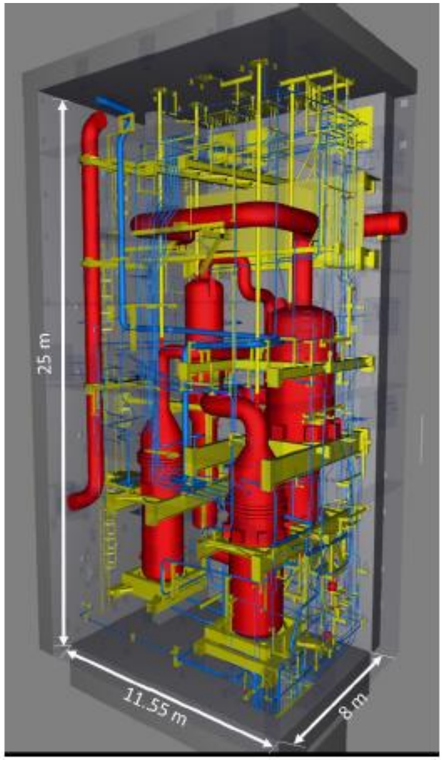
- Faces/surfaces have safety implications for scaffold/rope access, remote measurements advantageous.
- Simple structural geometries suitable for ROV.

Inspection (2) – Aerial Stacks

- Concrete curved stacks over 100ft high, diameters 2 -8 m at the base.
- Associated with ventilation systems for nuclear safety purposes. ROV minimises downtime if the internals are to be inspected by avoiding man access near to the outlet.
- ROV required to inspect the internals of an operational stack, with the associated air flows and velocities.
- External examination of stack expected.

Inspection 3 – Radiation Contaminated Reprocessing Cells

- Store plant, vessels, pipework and other devices
- Concrete and rebar construction - clad with stainless steel 2-3mm thick with a transition part way up the wall (if not fully clad)
- Floors clad with stainless steel, demanding a high friction medium for traction. Accumulations of dusts/loose debris are possible
- ROV introduced via man-access door or cell wall penetration
- Walls 200 to 1800mm thick
- Cell wall penetrations 150 to 200mm in diameter



Climbing Robot for inspection of large concrete structures e.g.

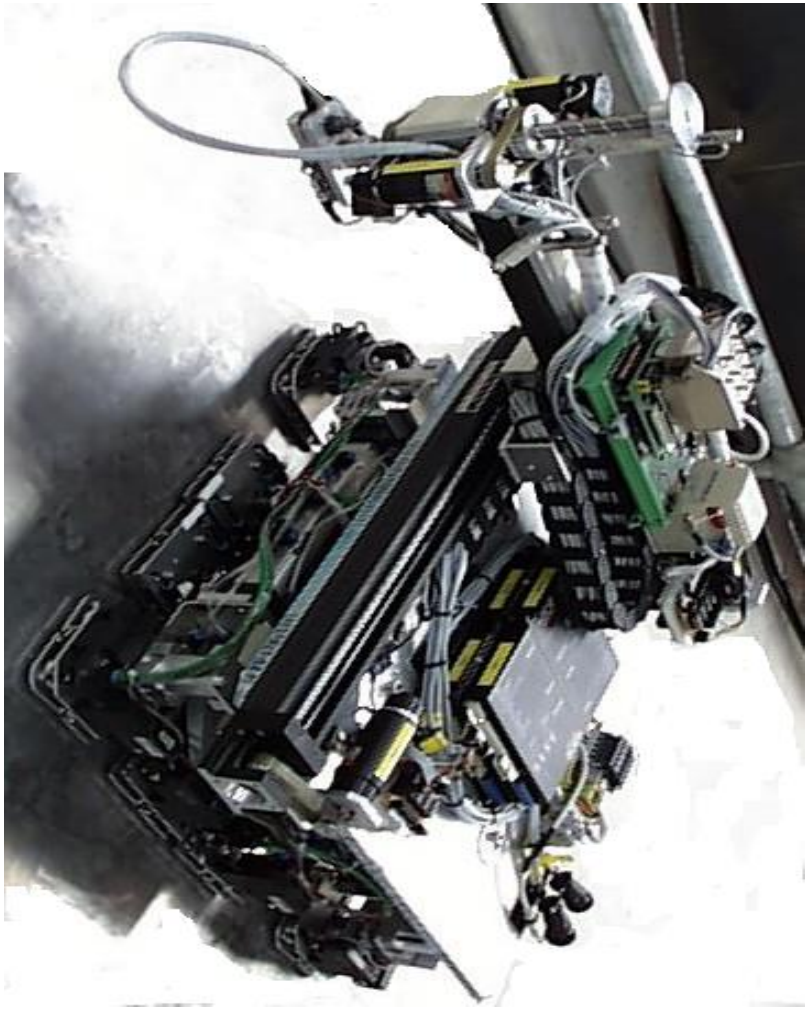
- Stacks
- Radiation Cells
- Buildings
- Civil engineering structures

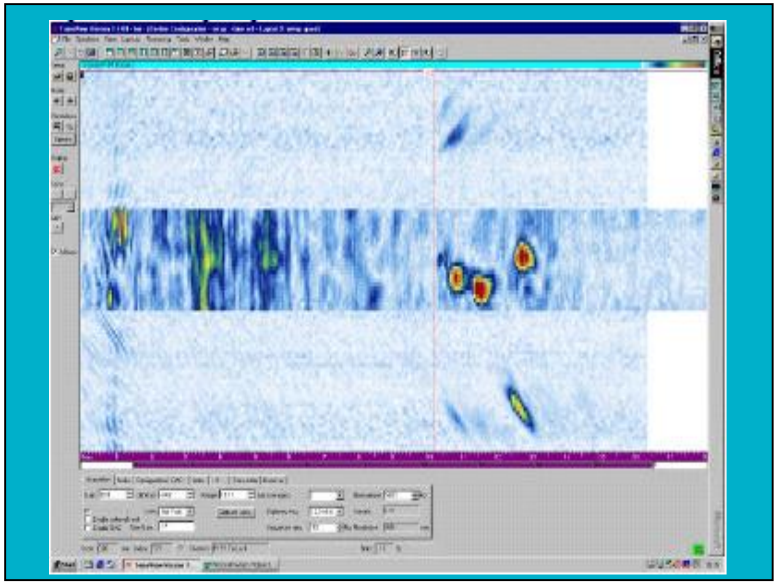
New InnovateUK project SIRCAUR

Demonstration of STRONGMAN carrying TWI laser cutting tool for nuclear decommissioning – 21 September 2016

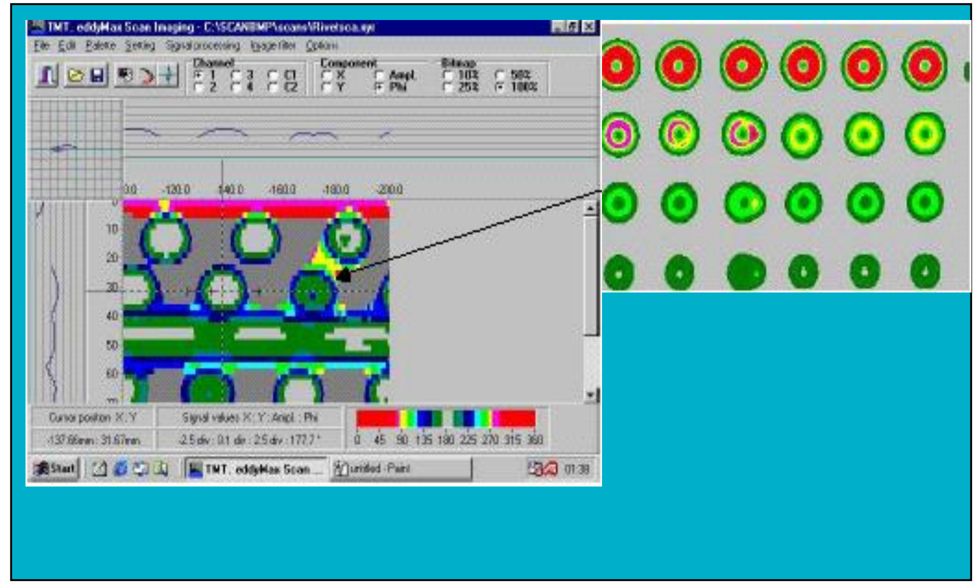
The Lasersnake2 R&D project funded by the UK Technology Strategy Board, the Department for Energy and Climate Change, and the Nuclear Decommissioning Authority is using snake arms to deploy laser cutting heads

Inspection of rows of rivets on aircraft wings and fuselage with a climbing robot

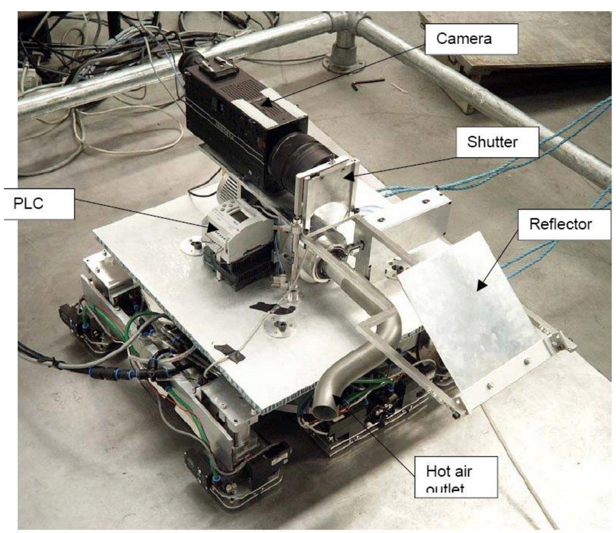


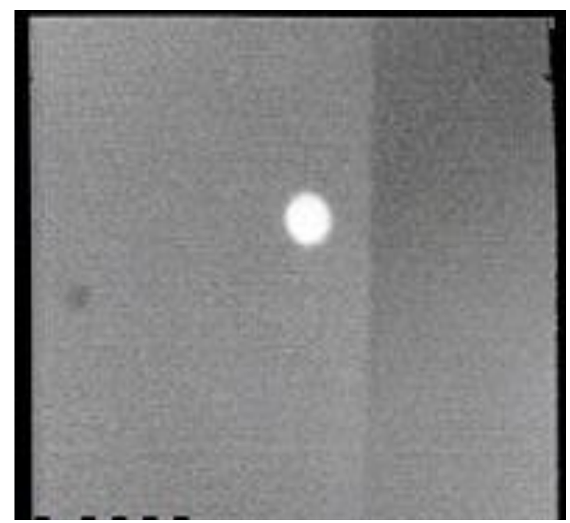


ULTRASONIC PHASED ARRAYS to inspect rivets on aircraft, ROBAIR project



EDDY CURRENTS inspection of rows of rivets on the wings and fuselage of aircraft, ROBAIR project



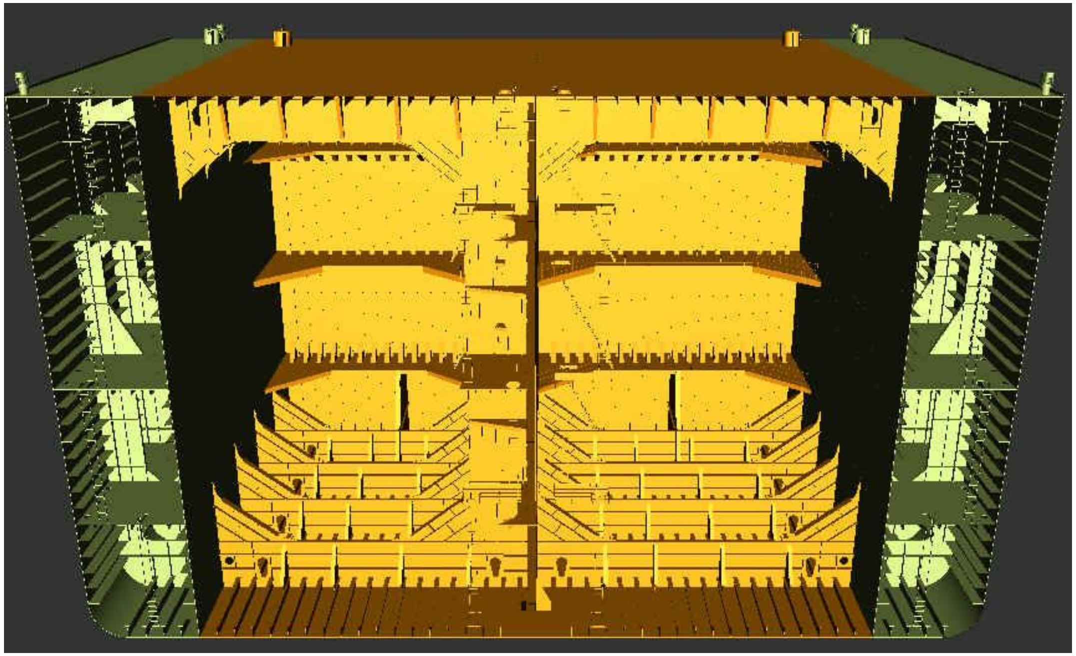


Thermographic detection of loose rivets

Floating Production Storage of Oil (FPSO)

Task: Inspect welds between strengthening plates and tank floor

- Outage required with cleaning of tank before inspectors can enter tank – problem of disposal of cleaning medium
- Eliminate outage by performing in-service inspection with mobile swimming robots or empty without cleaning and use amphibious robot



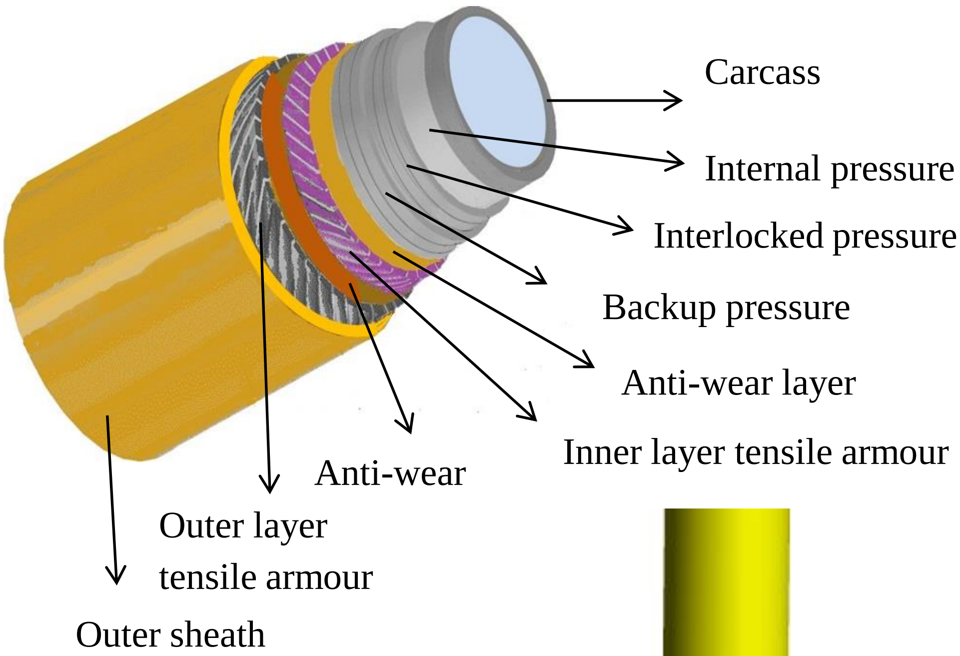
Two tanks are emptied, cleaned and inspected in 3-4 weeks with 60-70 man-days work and costs between £30-40k.

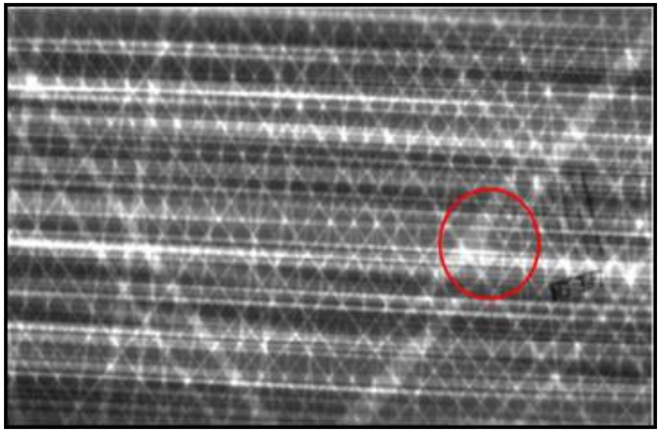
FPSO swimming and floor inspection robot to inspect tank floors and welds on strengthening plates

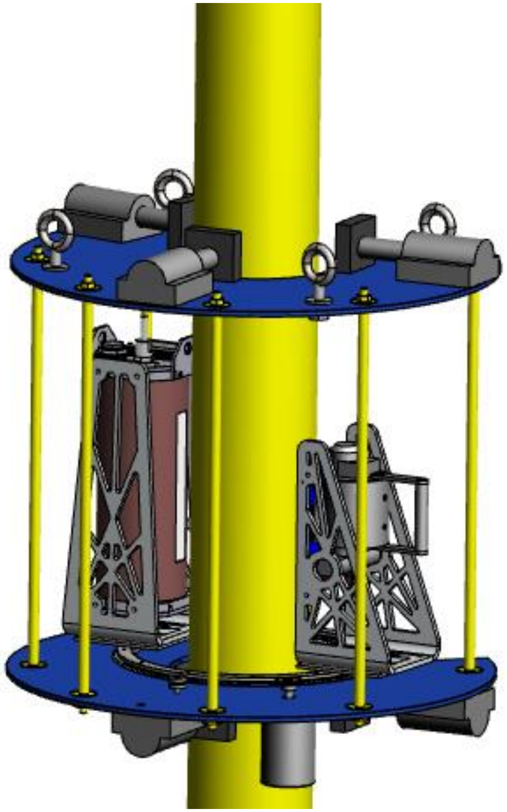
Horizon 2020-FTI Pilot-2015

RiserSure

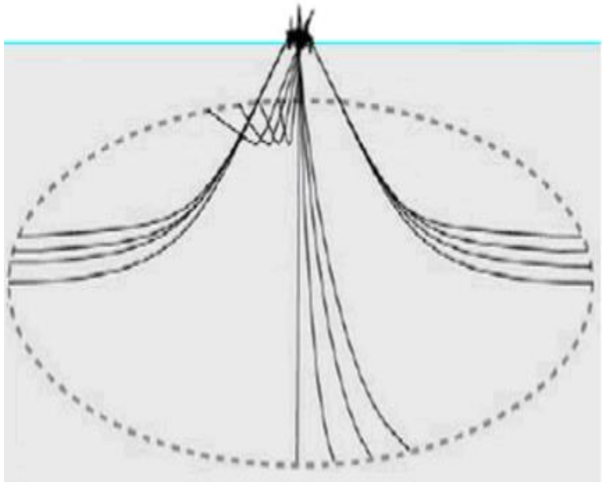
Rapid Integrity Assessment of Flexible Risers for Offshore Oil and Gas Installations with radiography



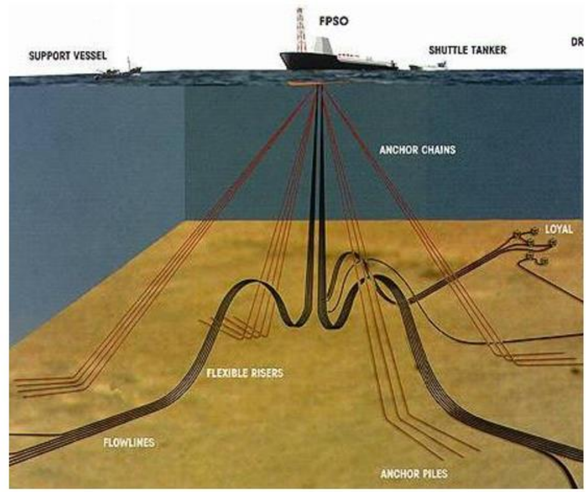




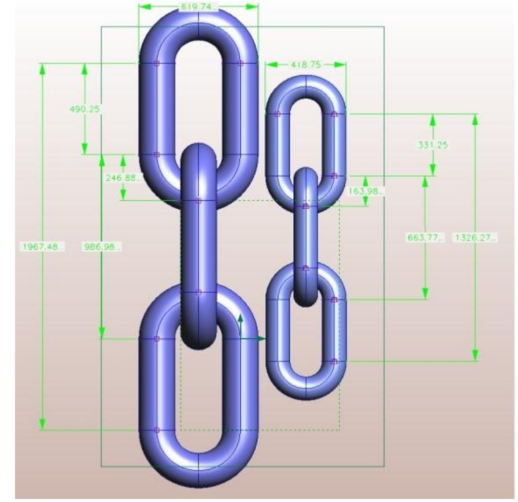
Mooring chains in shallow waters



Mooring chains in deeper waters

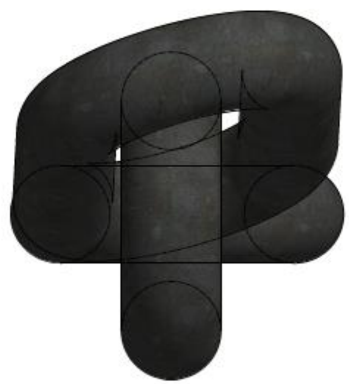


Link lengths 1 m to 0.7 m
Dia 160 - 130 mm



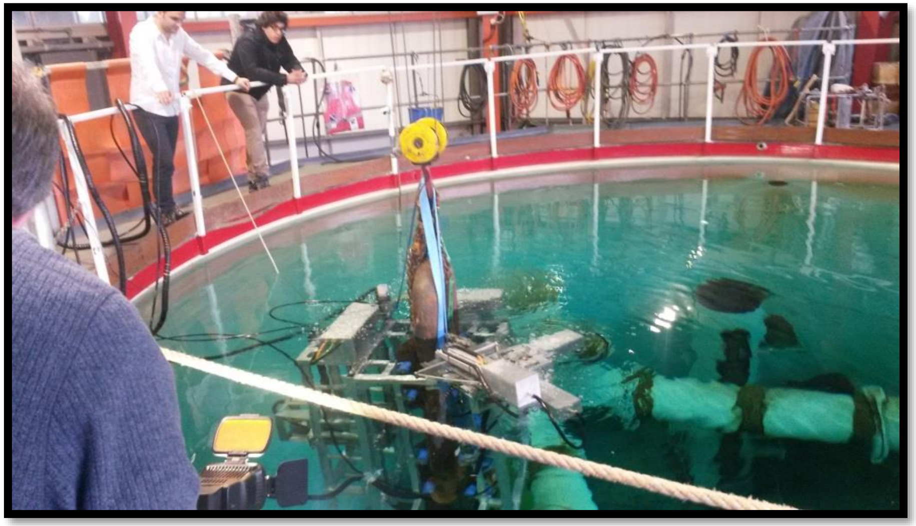
MOORING CHAINS

Link twist

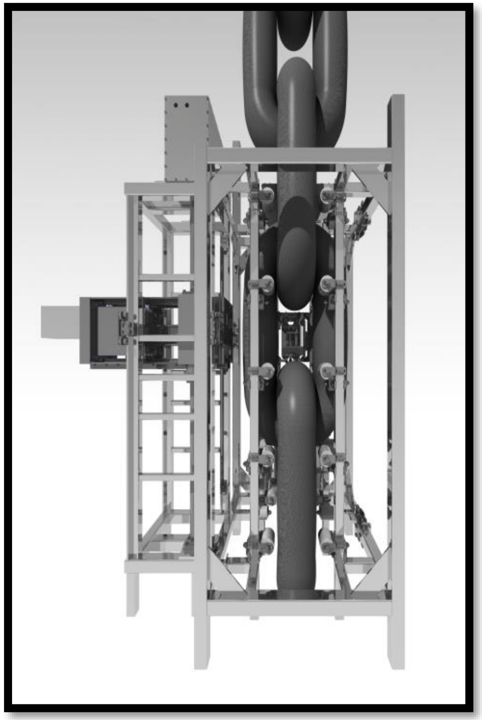


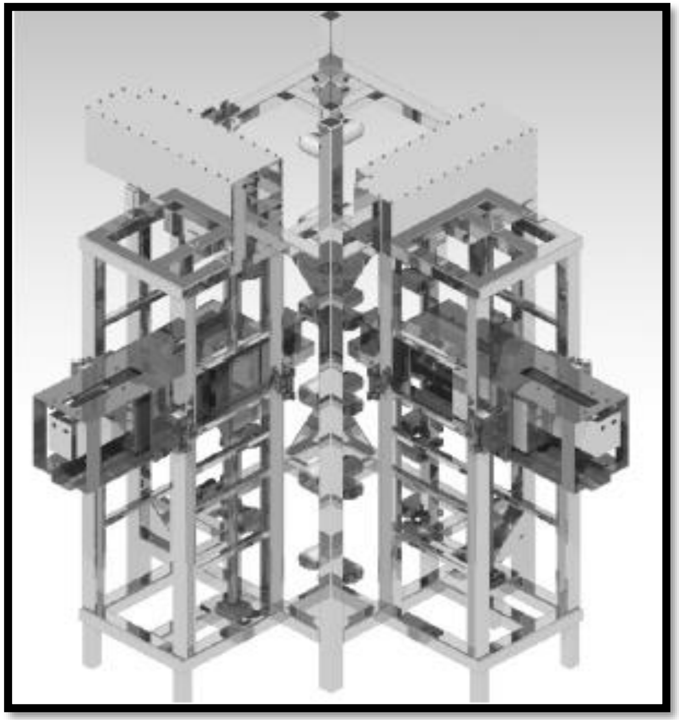
Link twist plus curve

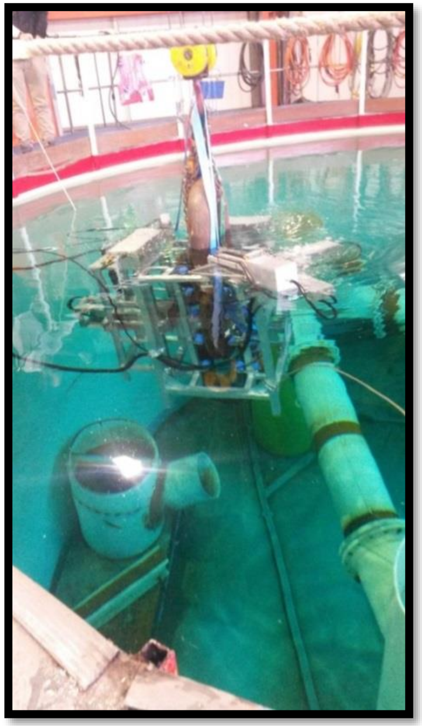
Catenary curve in chain



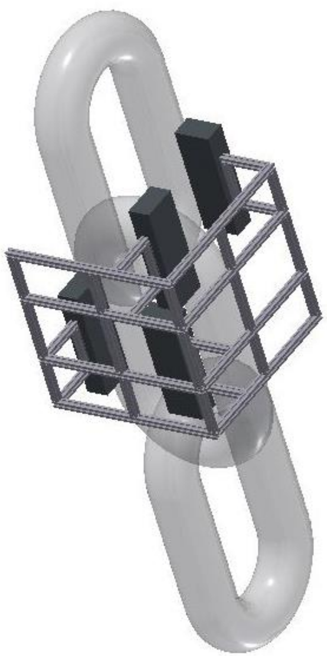
FP7-SME The MOORINSPECT PROJECT→ InnovateUK/EPSRC project RIMCAW

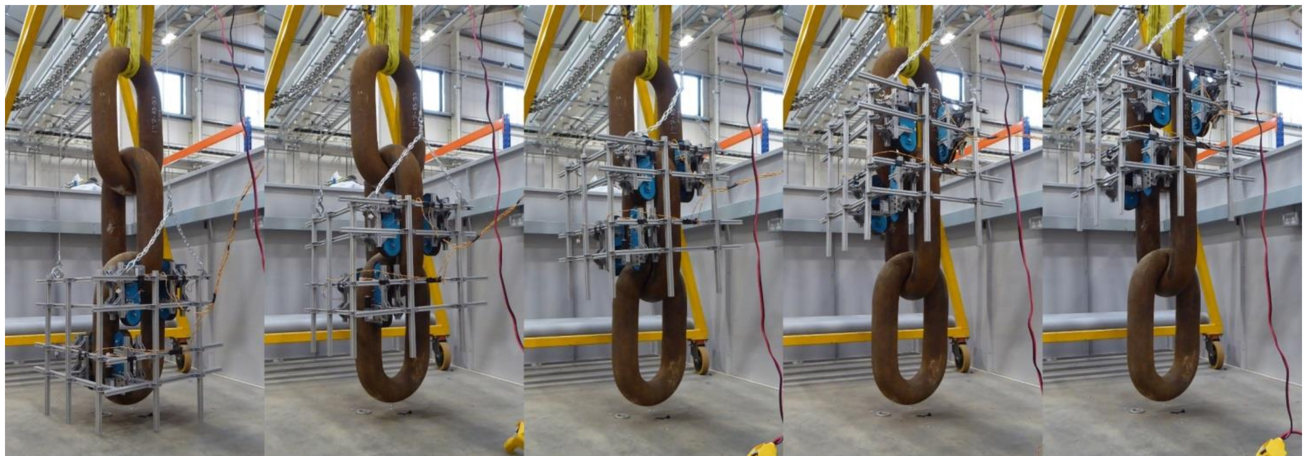


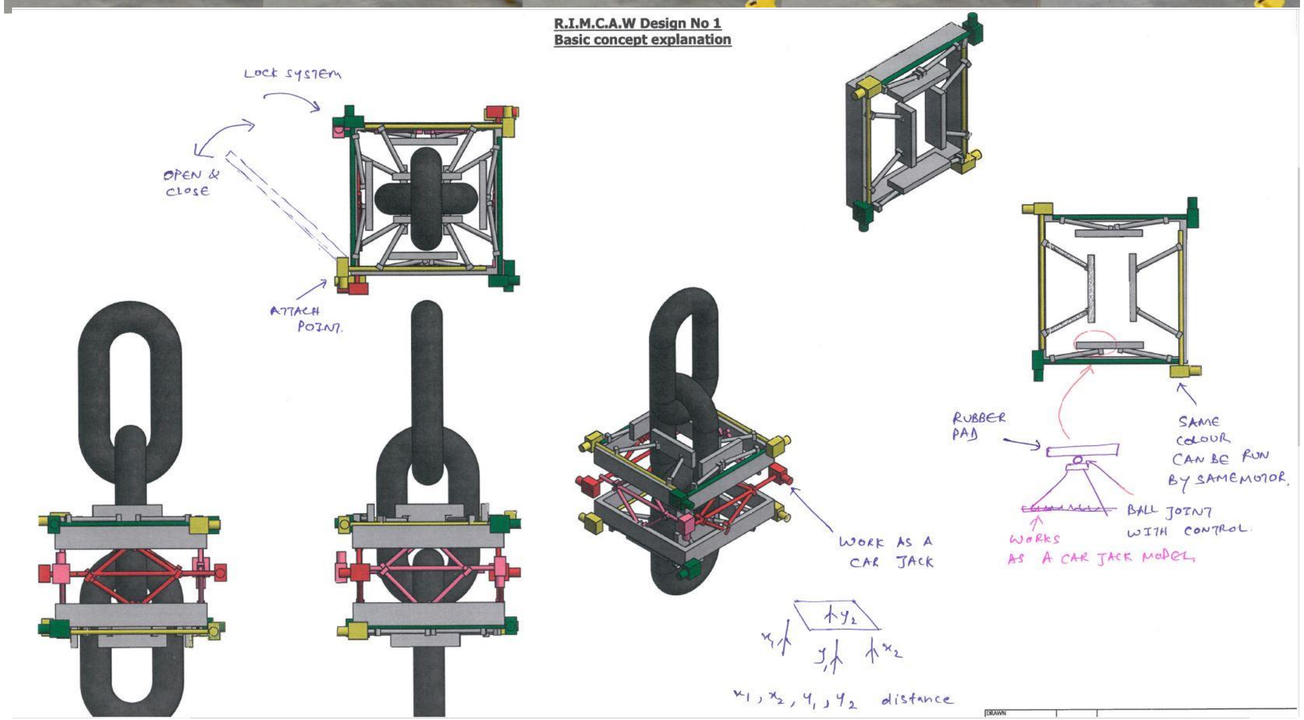




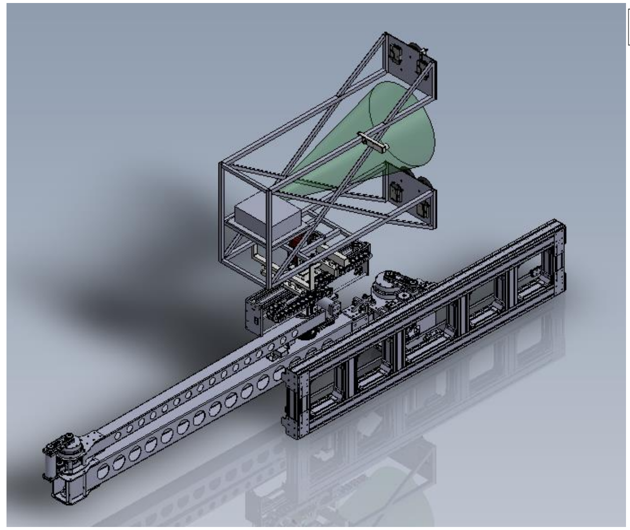
New InnovateUK project RIMCAW: Robotic Inspection of Mooring Chains in air and water

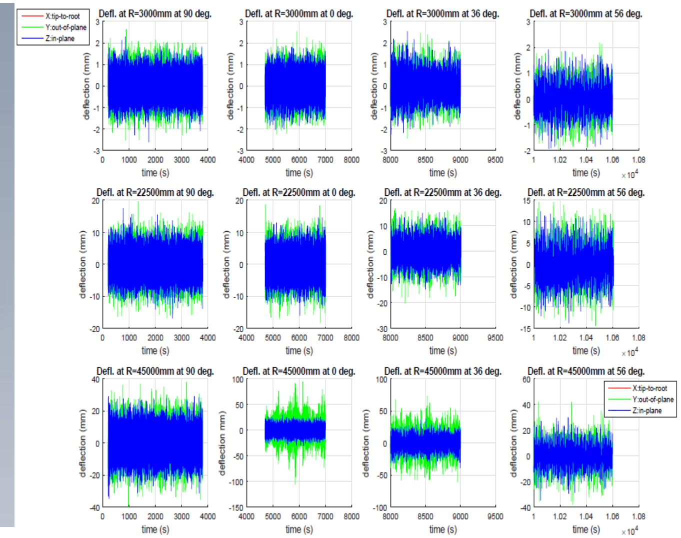






Climbing robots for monopile, wind turbine tower and blade inspection



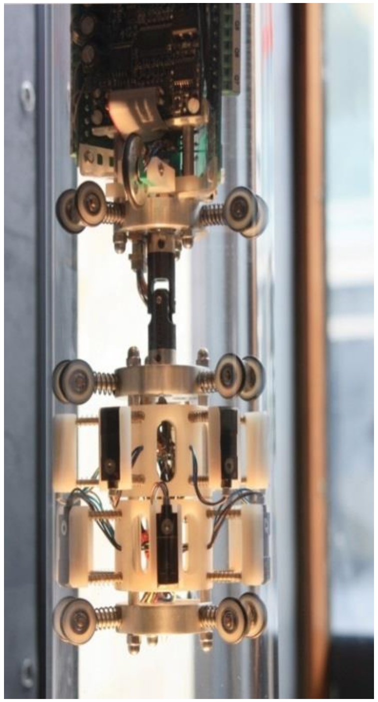


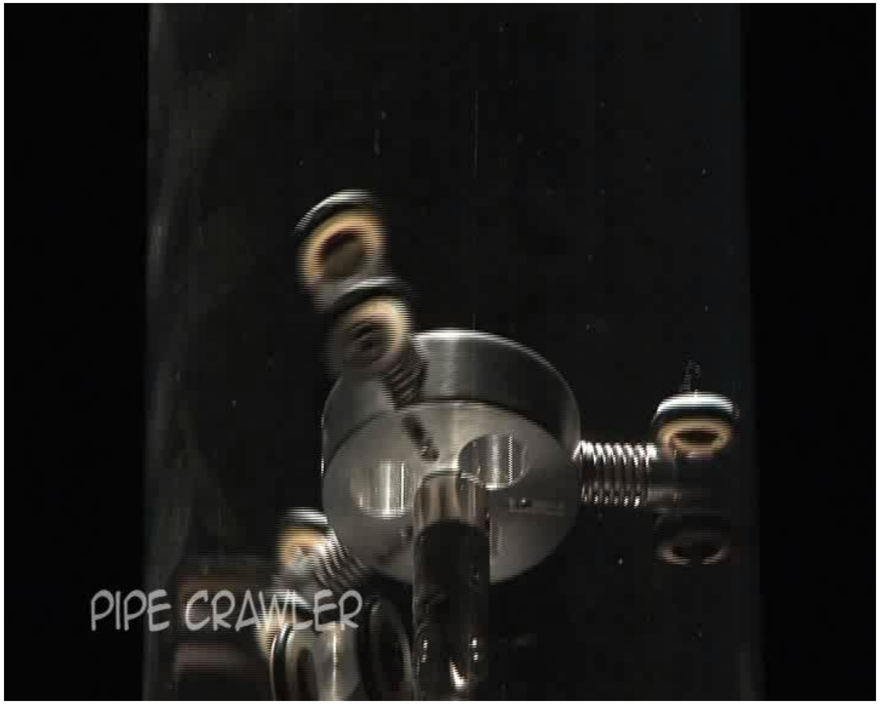
H2020 FTI project WINSPECTOR uses shearography to NDT blades

FP6 project to NDT blades uses X-ray computed tomography to NDT blades

New InnovateUK project RADBLAD X-ray radiography of NDT blades with robots

Pipeline inspection - pipe climbing robot





New InnovateUK project FSWBot to internally inspect and weld repair pipelines with robots

London
South Bank
Innovation Centre

Conclusion

Mobile robots that can access safety critical infrastructure located in remote and extreme environments promise to

- Ensure the integrity of assets
- Reduce inspection and maintenance costs
- Reduce outage turn-around time/ perform in-service NDT
- Increase worker health and safety and reduce fatalities