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Wireless Charging of Permanently Deployed Autonomous Deep-Sea HyDrones

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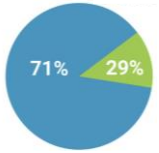
Abstract — Future far-offshore floating windfarms and/or floating solar power plants in combination with hydrogen production and economic energy transport by molecules instead of electrons utilizing former oil/gas pipelines, as well as repurposing off-shore platforms and decommissioned oil/gas wells as part of CO2 capture and storage systems are key elements of a transition to green energy generation, industry decarbonization and finally a sustainable society. Aquacultures are another fascinating sector of the Blue Economy and of major future importance considering that oceans cover over 70% of the earth´s surface. In this context, advanced technologies for the installation, integrity inspection and maintenance of the newly built infrastructures will massively gain in importance. Examples are unmanned “Hydrones”, i.e., tethered Remote Operated Underwater Vehicles (ROVs) and un-tethered / battery-powered Autonomous Underwater Vehicles (AUVs) capable of operating for extended periods of time without being recovered to the surface and accordingly reducing risks, weather dependence and costs.

The talk will first introduce main future sectors of the Blue Economy and discuss the concept and basic challenges of ROV technology including the vehicle power supply over long distances down into the deep and the operation in extreme pressure environments and show examples of recently developed electric work-class industrial ROVs. Next, challenges of the wireless re-charging of seabed resident AUVs, like eddy current losses due to the conductivity of seawater and biofouling, i.e., the accumulation of marine microorganisms on the charging port surface, as well as various coil arrangements and docking/charging port geometries and the utilization of the magnetic field for landing the AUV precisely on the charging platform will be described. Furthermore, moored local surface wave energy generator systems floating over the point of use, which allow to eliminate a charging system power umbilical running back to a surface support vessel or to the shore and/or provide full autonomy are briefly discussed. In addition, an example of a first industrial AUV docking station, integrating an up to 5kW wireless charging system qualified for subsea applications 3000m below the surface and featuring simultaneous power and data transfer capability and an efficiency of 95% will be shown. Finally, the vision of an underwater version of the International Space Station, PROTEUS, proposed by the grandson of Jaques-Yves Cousteau, which aims to generate a livable space for scientists and should allow the testing of advanced technologies for green power, aquaculture, and robotic exploration is described and topics for future research in the area are highlighted.

Outline

- *Introduction*
- *ROVs / AUVs*
- *Wireless Charging of AUVs*
- *Built System*
- *Outlook*

Blue Economy



Source: toppr.com

Off-Shore ...

- Windfarms
- PV Power Plants
- Green H_2 Production
- CO_2 Storage
- Energy Storage
- Subsea Industries

Blue Economy

- Economic Sectors Related to Exploitation / Preservation / Regeneration of Marine Environment
- Established Sectors — Maritime Transport | Ship Building | Fishing | Off-Shore Oil & Gas | Coastal Tourism | etc.

Source: EU Science Hub

- Highlighted Emerging Activities — Floating Off-Shore Wind & Solar Energy | Wave & Tidal Energy | Robotics etc.
- Important Role in the EU´s Transition Towards a Carbon-Neutral / Circular / Biodiverse Economy

Floating Off-Shore Wind Power Plants

- 80% of Off-Shore Wind Energy Available in Deep Waters
- Higher & More Consistent Wind Speeds / Lower Environmental Impact

Source: Josh Bauer / NREL

- Floating Support Structures for Seabed Depths > 60m — Seabed Connection Through Mooring Cables
- 3 Basic Types — Tower-Like Spar Buoy | Semi-Submersible | Tension Leg (Mooring Cables Under Tension)

Floating Off-Shore Solar Plants

- 10x Growth of Solar Power to 5 TW Mandatory for Closing the Emission Gap
- Dense Population / Land Shortage → Utility-Scale Solar Projects on Inland Waters and in Oceans
- Potential Combination of Off-Shore Wind & Off-Shore Solar Infrastructures

Source: www.rechargenews.com

- Higher Sun Irradiance @ Sea & Lower Temperature / Higher Efficiency
- Destructive Wind & Wave Forces → Membrane-Type Flexible Circular Platforms w/ Buoyancy Rings
- Potentially Lower Cost of Off-Shore Solar Compared to Off-Shore Wind — 2x Higher GWh/km^2

Off-Shore Green-H_2 Production

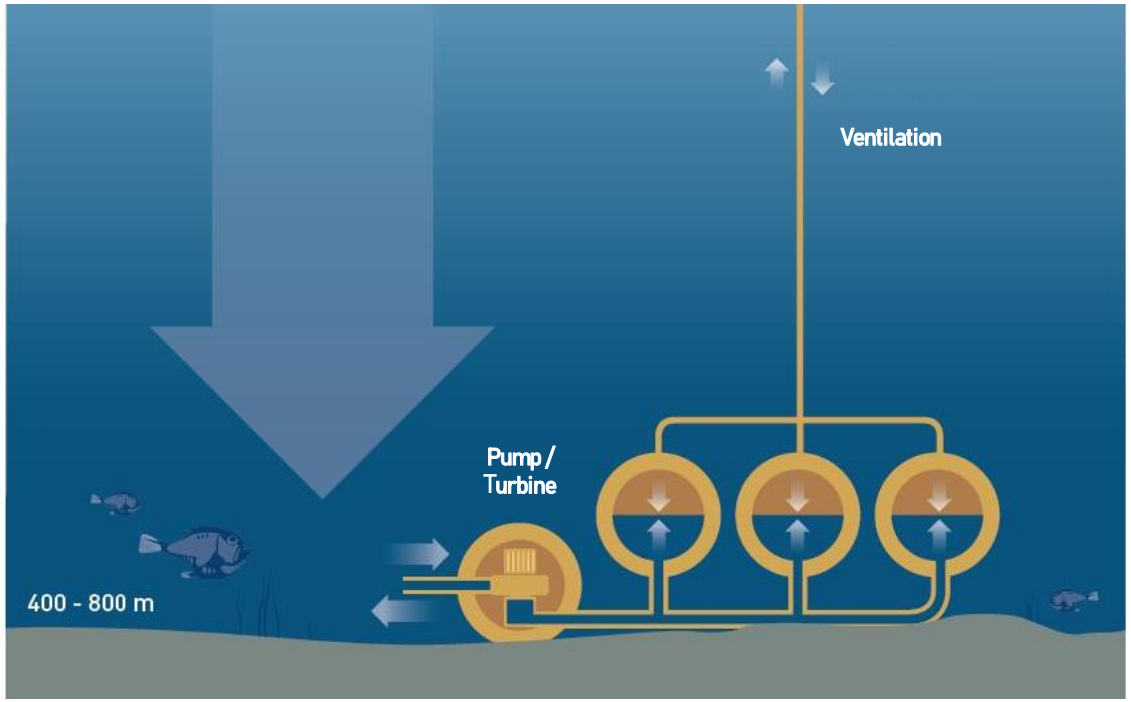
- Energy Transport via Molecules / Hydrogen Avoids High $$$ of HVDC Cables / Systems
- Decline of Oil & Gas Production → Repurposing of Offshore Assets / Platforms, Pipelines etc.

Source: https://tractebel-engie.com

- P2G → Desalinated H_2O Electrolyzers on Off-Shore Platforms Converting Wind Energy to "Green Hydrogen"
- 60-80% Conversion Efficiency / Multi-GW Scale / Interconnection of Neighboring Countries

Subsea Pumped Hydro Storage

- GWh-Scale 10MWh-Modular / Scalable Storage @ Seabed Exploiting the High Deep-Sea Pressure
- Off-Shore Installation Near Wind Farms / Floating Solar Farms / Tidal & Wave Energy Systems etc.

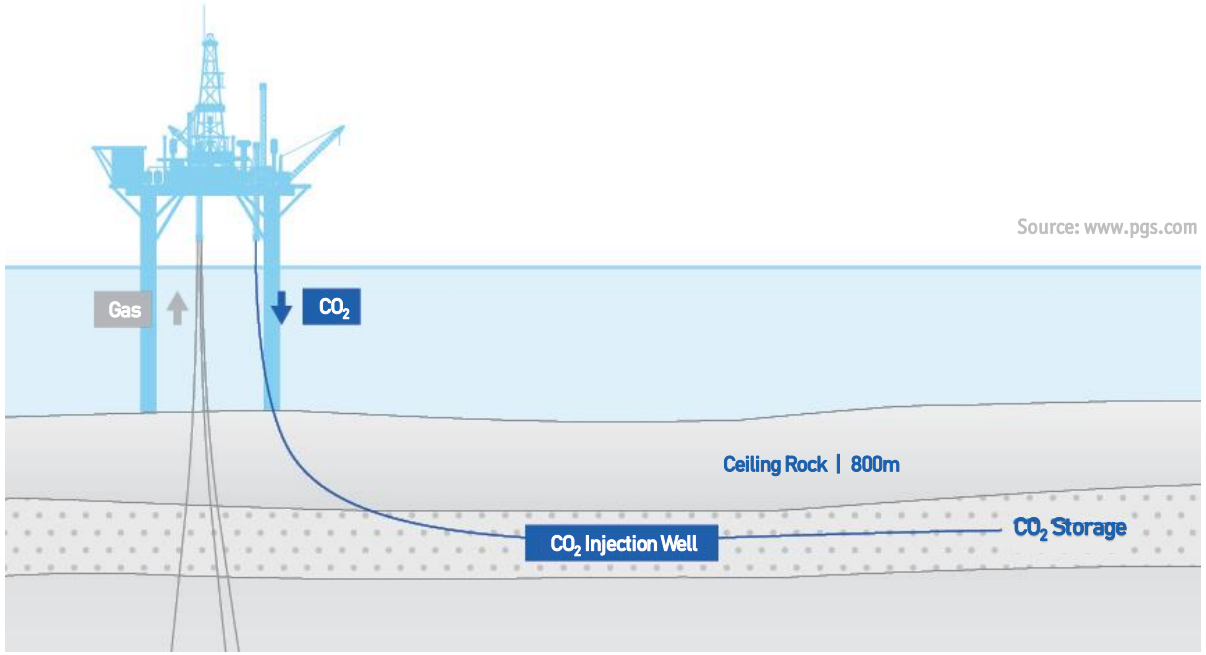


Source: SINTEF

- Charging → Pumping Water from Low-Pressure Rigid Reservoir Into High Pressure Environment
- Discharging → High Pressure Environment Pushes Water Into Reservoir / Drives Turbine

Off-Shore CO_2 Storage

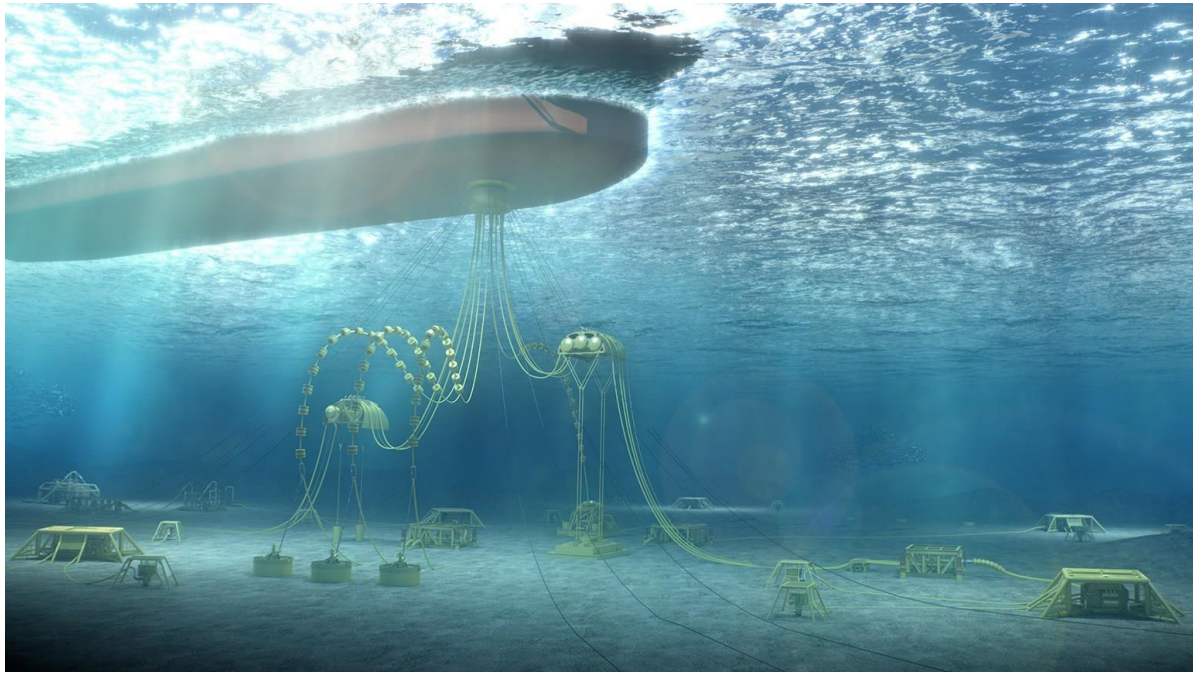
- CO_2 Capture & Storage (CCS) → Main Element of the Energy Transition to a Low Carbon Future
- Future Industrial CCS Value Chain → CO_2 Transported by Ships & Stored in Off-Shore Formations



- World´s 1st Off-Shore CCS Plant in Operation since 1996 in Sleipner Natural Gas Field (Equinor = Statoil)
- Norwegian CO_2 Tax Introduced 1991 → CO_2 Contained in Natural Gas Re-Injected Into Porous Sandstone

Subsea Industry / Autonomous Factories

- Deep-Sea Oil & Gas Extraction / Processing — No Platforms / Lower $$$ | Deep-Sea Mining
- Lower Environmental Impact of Natural Gas Compared to Coal → "Golden Age of Gas"

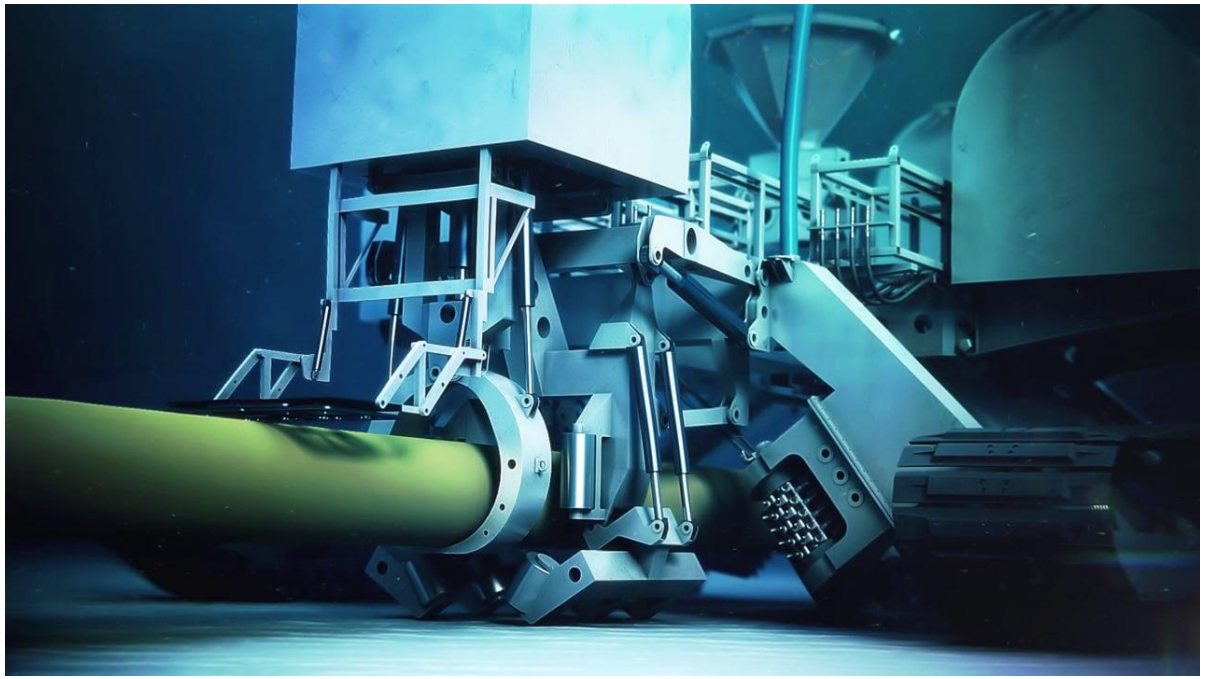


Source: www.ocean-5.com

- Hydraulic Wells → High Eff. All-Electric Wells → No High Pressure Equipm. / No Pipe Leaking / Lower $$$
- Long Distance DC Power Transmission (600km, 100MW, 3000m) → Pumps etc. Located @ Seabed

Seabed Interventions – 1/2

- Burial of Subsea Pipelines and Cables
- Jet Trenching ROVs | Ploughs | Mechanical Trenchers — x 1000m Operation Depth



Source:
DEEPOCEAN

- World´s Most Powerful Trencher (T3200 / 2.4MW / DeepOcean)

Seabed Interventions – 2/2

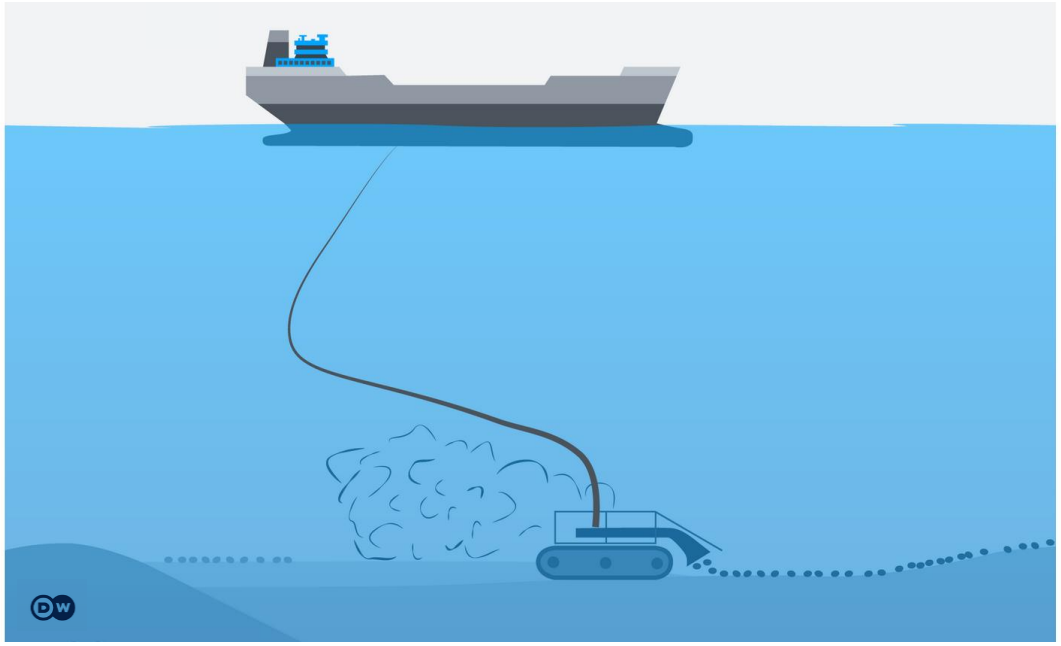
- Burial of Subsea Pipelines and Cables
- Jet Trenching ROVs | Ploughs | Mechanical Trenchers — x 1000m Operation Depth

Source: DEEPOCEAN

- World´s Most Powerful Trencher (T3200 / 2.4MW / DeepOcean)

Deep-Sea Mining Vehicles – 1/2

- Suction of Polymetallic Nodules (Mn, Co, Cu, etc.) @ Seabed (4000…6000m)
- Subsea Crushers & Pumps for Transportation of the Minerals to Supporting Vessel



Source: www.hydrographica.org

- Potential Serious Threat to Global Oceans (!)

Deep-Sea Mining Vehicles – 2/2

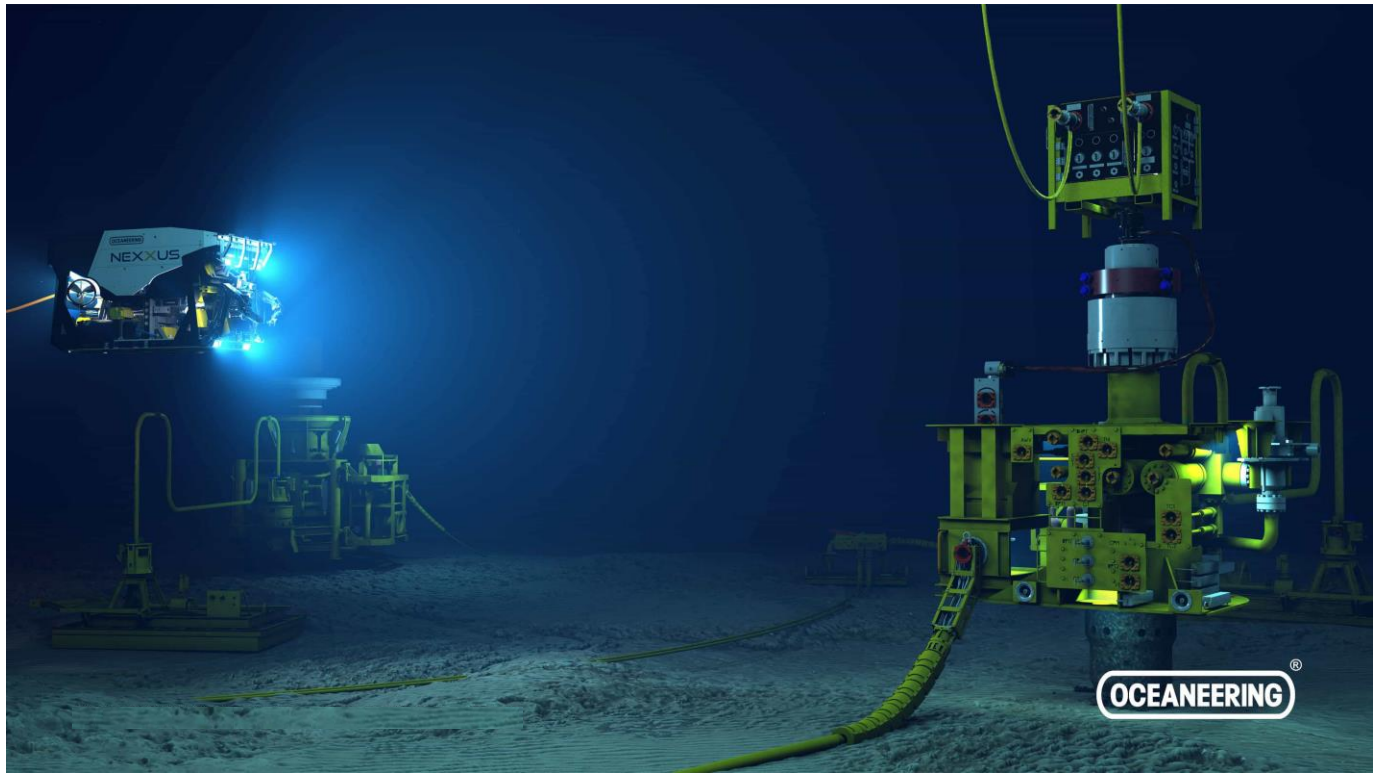
- Suction of Polymetallic Nodules (Mn, Co, Cu, etc.) @ Seabed (4000…6000m)
- Subsea Crushers & Pumps for Transportation of the Minerals to Supporting Vessel

Source: GSR

- Patania II 25t Robot "Nodule Collector" (Tested @ 4500m)

Subsea IMR — Inspection / Maintenance / Repair

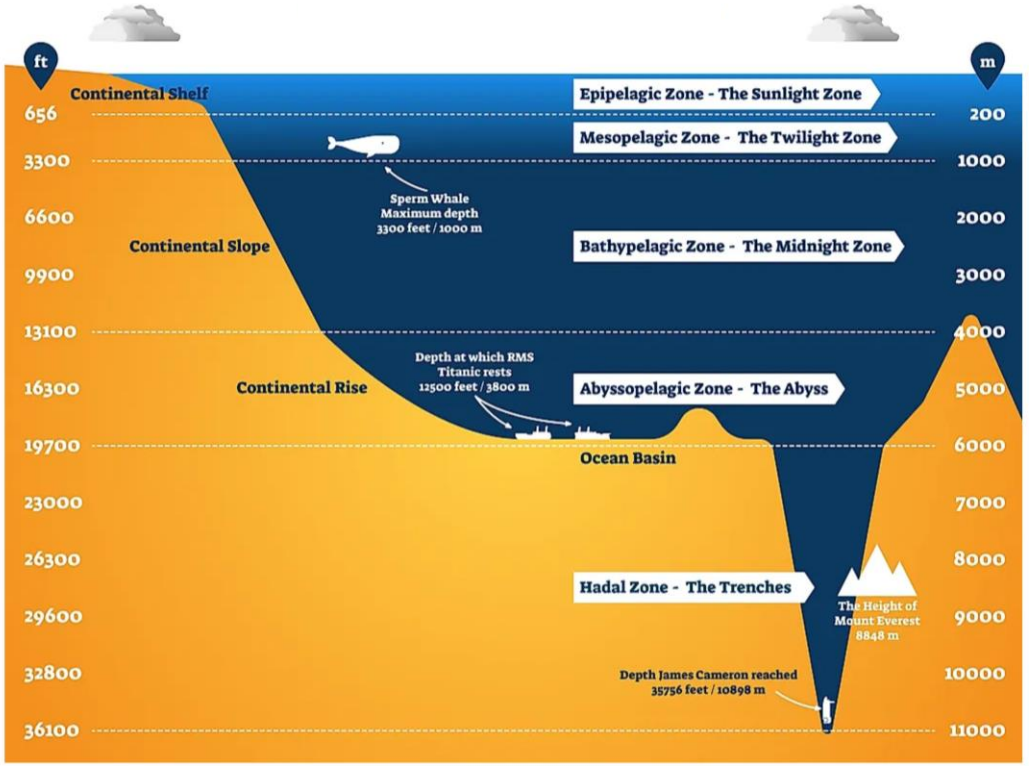
- Complex / Inaccessible Subsea Infrastructures → Inspections & Interventions
- Oil & Gas Industry → Well & Infrastructure Diagnostics | Remediation of Damaged Wells etc.



- Operation Depths > 2500 m

Scientific Exploration of Ocean Depths

- Surveys of Submarine Volcanoes / Hydrothermal Vents / Subduction Zones
- Collection of Seabed Sediments / Microorganisms



▼ Deep Ocean

Source: VectorMine/Shutterstock.com

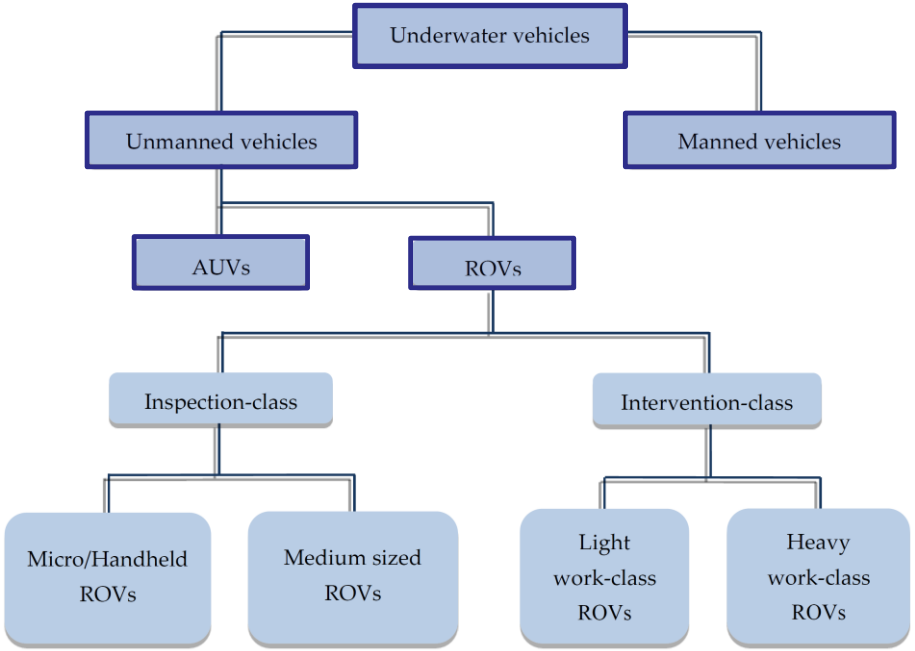
- 5 Zones / Deepest Location → "The Challenger Deep" @ 11´034m (≈ 4°C) | 3´700 m in Average

ROVs / AUVs

Classification
Power Supply

Classification of Underwater Vehicles – 1/2

- ROV — Remotely Operated Underwater Vehicle | Connected to Surface Vessel via Umbilical
- AUV — Autonomous Underwater Vehicle



Source: Capocci, et al. / 2017 MDPI

- Global Annual ROV Market — $3.5 Billion in 2020 / 11.5% CAGR in 2021...2026 RESEARCHANDMARKETS THE WORLD'S LARGEST MARKET RESEARCH STORE
- 74% Increase in AUV Demand in 2022

Classification of Underwater Vehicles – 2/2

- ROV — Remotely Operated Underwater Vehicle | Connected to Surface Vessel via Umbilical
- AUV — Autonomous Underwater Vehicle

Source: SCHMIDT OCEAN INSTITUTE

- Global Annual ROV Market — $3.5 Billion in 2020 / 11.5% CAGR in 2021...2026 RESEARCHANDMARKETS THE WORLD'S LARGEST MARKET RESEARCH STORE
- 74% Increase in AUV Demand in 2022

Work-Class ROV

- Thrusters / Manipulators / Instruments
- Lights / Video Camera

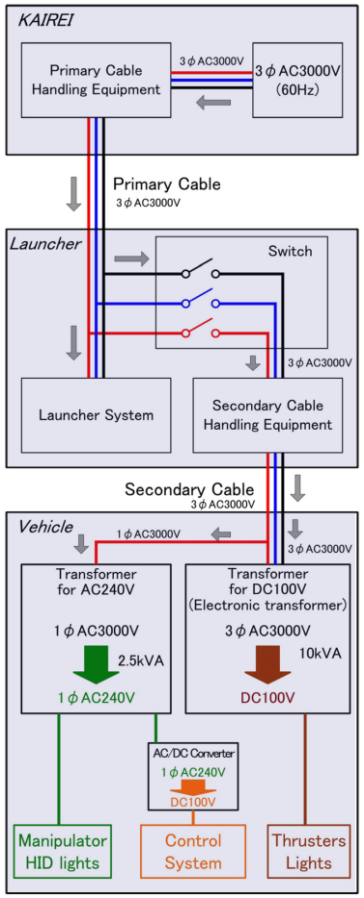
SPECIFICATIONS	
Depth rating	3000 msw (option to 6000 msw)
Length	2200 mm
Height	1500 mm
Width	1325 mm
Launch weight	2100 kg
Forward speed	> 3 knots
Thrust forward	325 kgf
Thrust lateral	290 kgf
Thrust vertical	225 kgf
Payload	225 kg
Through frame lift	1 Te
Tooling circuit	24 kW
Manipulator circuit	5 kW
Instrumentation power - 24 VDC	2 kW
Instrumentation power - 110 VAC, 50 Hz	2 kW
Depth accuracy & resolution	0.01% / 1 x 10^{-8}
Heading accuracy & resolution	±1° / 0.351°

Source: SAAB

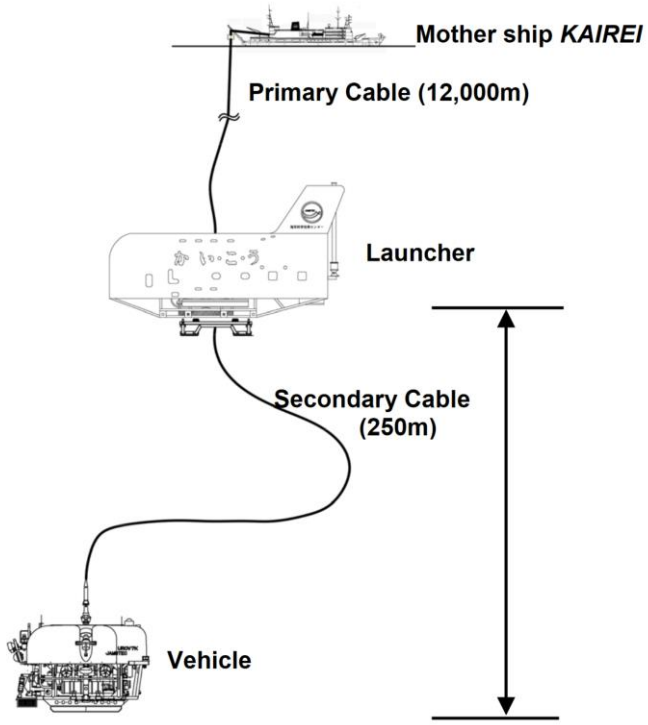
SYSTEM POWER REQUIREMENTS	
Input	3-phase 380-480 VAC, 50/60 Hz
ROV + Tooling	75 kVA
TMS	8 kVA
TMS propulsion (option)	28 kVA
LARS (typical)	150 kVA

- TMS — Tether Management System
- LARS — Launch and Recovery System

Work-Class ROV AC Power Supply System



Source: Murashima et al, 2005



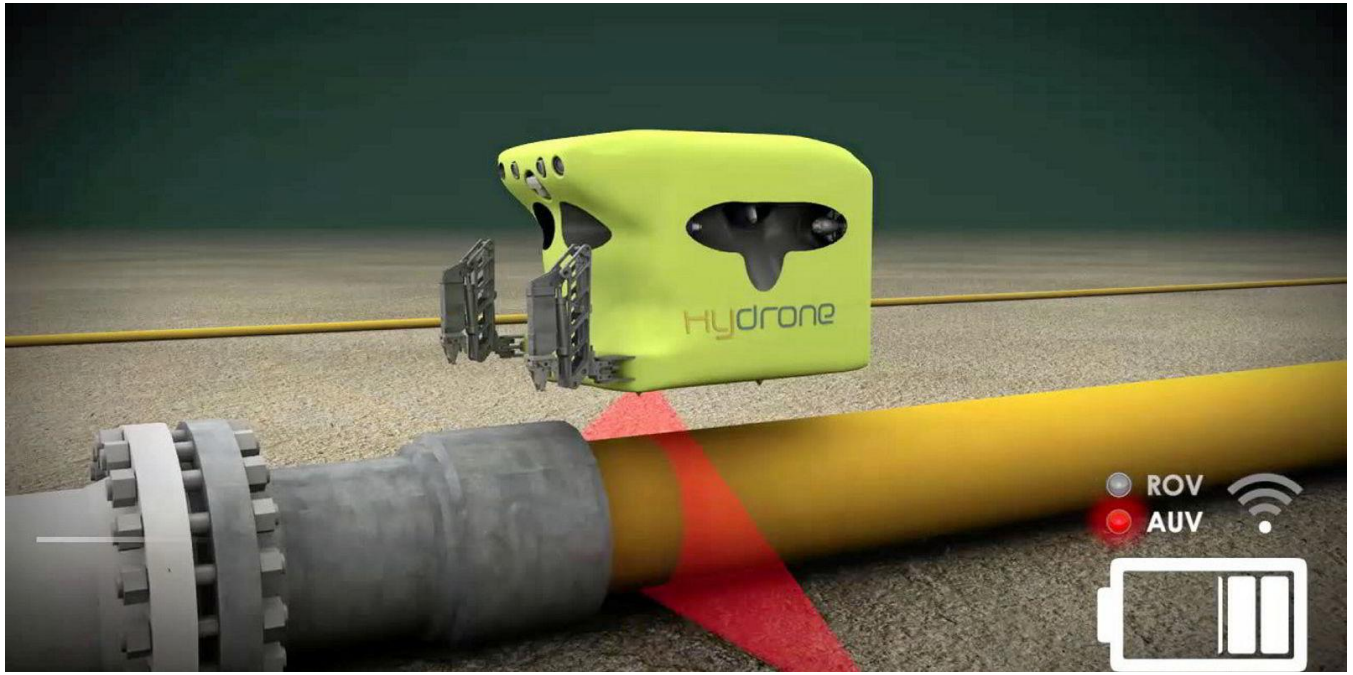
Source: Murashima et al, 2005

- 3-Φ AC 3000V / 60Hz Primary & Secondary Cable
- 1-Φ AC 240V & DC 100V @ Vehicle
- Passive XFRM & 30kg Electronic XFRM

- KAIKO 7000 Electric Power System

Autonomous Underwater Vehicles — AUV

- Self-Powered & Self-Guided → No Tether or Line to Crewed Surface Ship / Lower Mission $$$ etc.
- Mission Range & Duration Limited by Onboard Battery Capacity



Source: SAIPEM

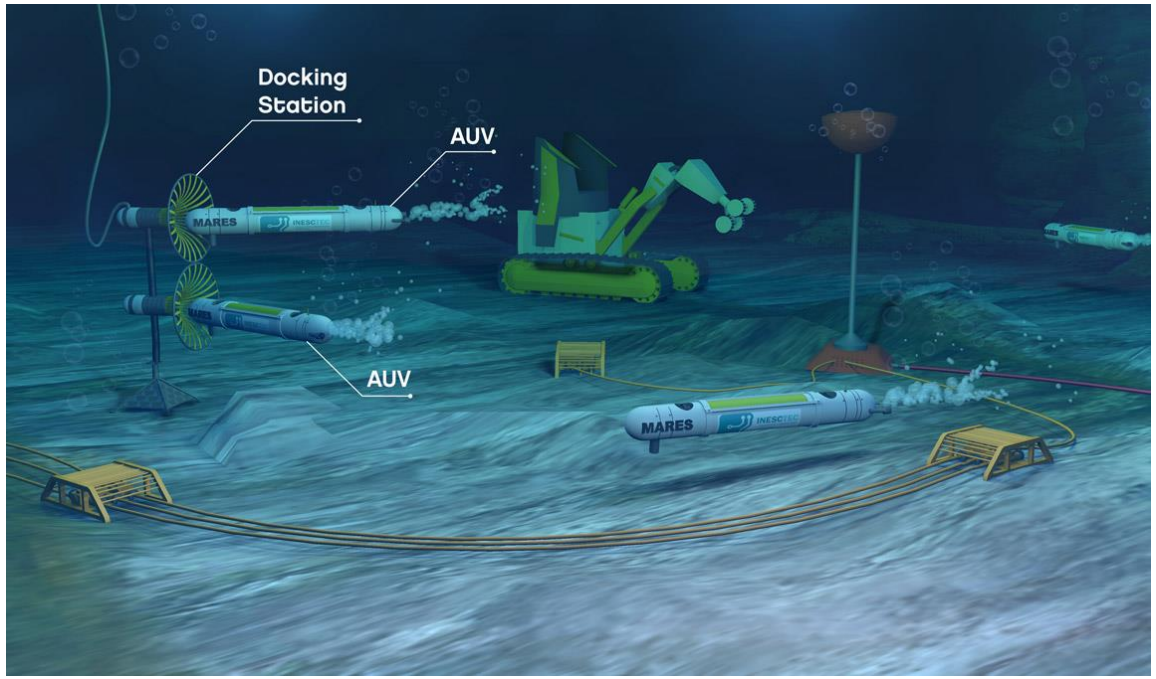
- Seabed Docking Station for Battery Recharge / Mission Download & Data Offload → Enables Subsea Residency
- Local Power Generation & Surface Communication | Unmanned Surface Vehicle for Launch & Recovery

Wireless Charging of Subsea Resident AUVs

Challenges
Proposed Concepts
Built Systems

Deep-Sea AUV Recharging in Remote Ocean Areas

- Inductive / Resonant IPT Couplers Integrating Contactless (!) Power Transfer & 2-Way Communication
- Funnel-Type OR "Landing-on-Base" Docking Stations

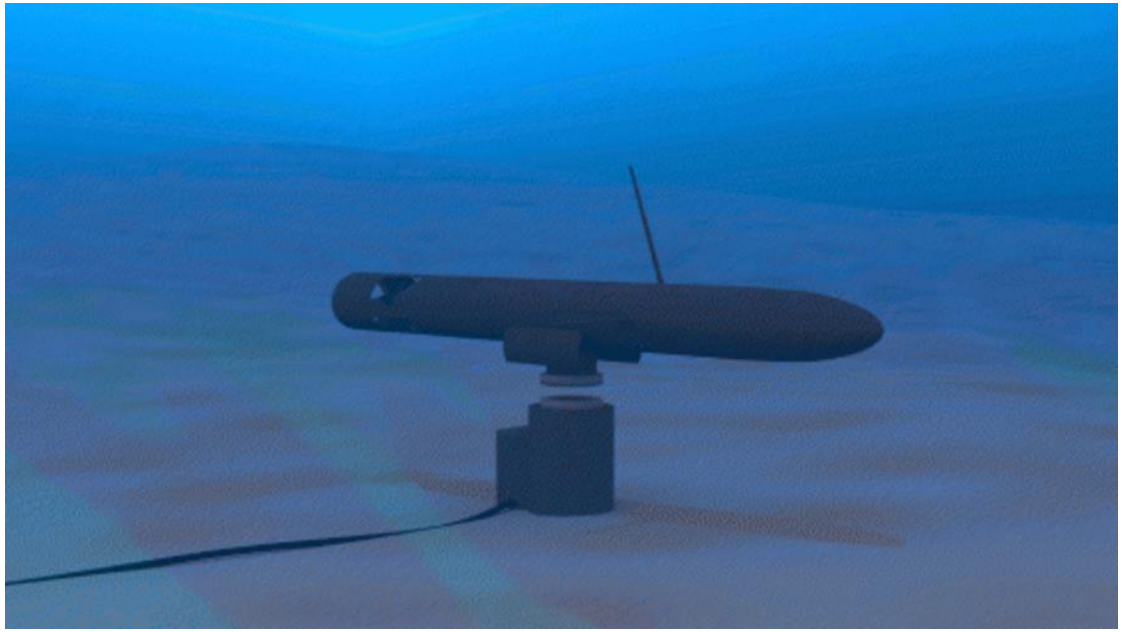


Source: EDURE

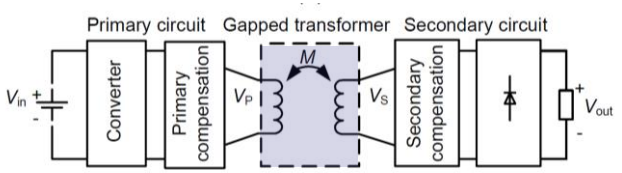
- Seawater Conductivity (≈3 S/m @ ≈3.5% Salinity) → Eddy Current Losses at Higher Frequencies
- Water Currents / Turbulence & Biofouling → Potential Dynamic Coil Misalignment / Larger Airgap

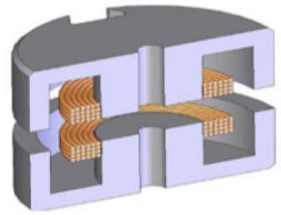
Wireless AUV Charging — Split-Core Transformers – 1/2

- " Wet-Mate"-Connectors / Direct El. Contact Replaced by Split-Core Transformers → Higher Reliability
- Sub-cm Airgap / High Coupling Coefficient → High Efficiency & Confined Magnetic Field / Low EMI
- Inductive Coupling Used for Power Transfer & Communication



Source: US Navy



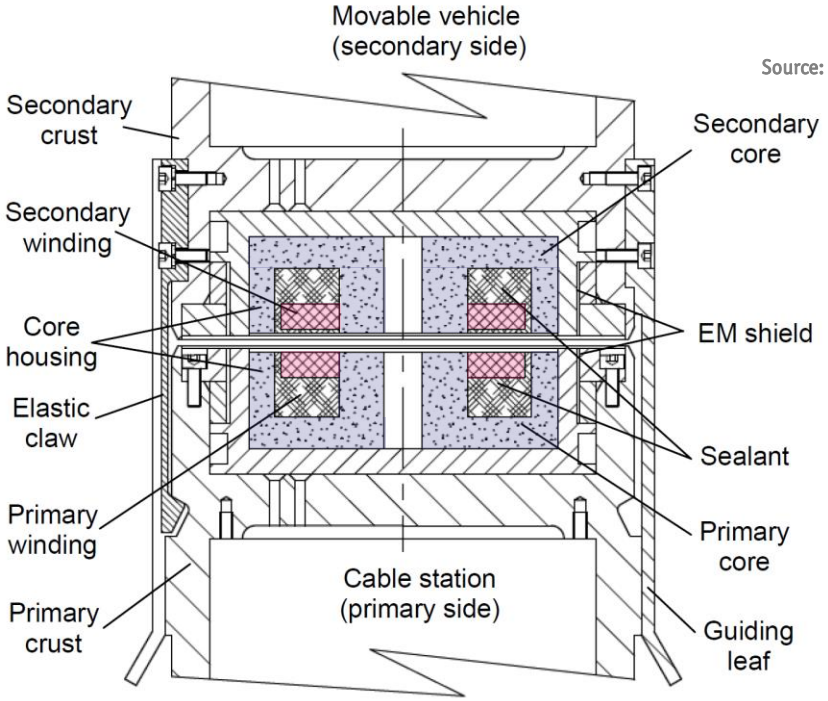


Source: Ze-song Li, 2010

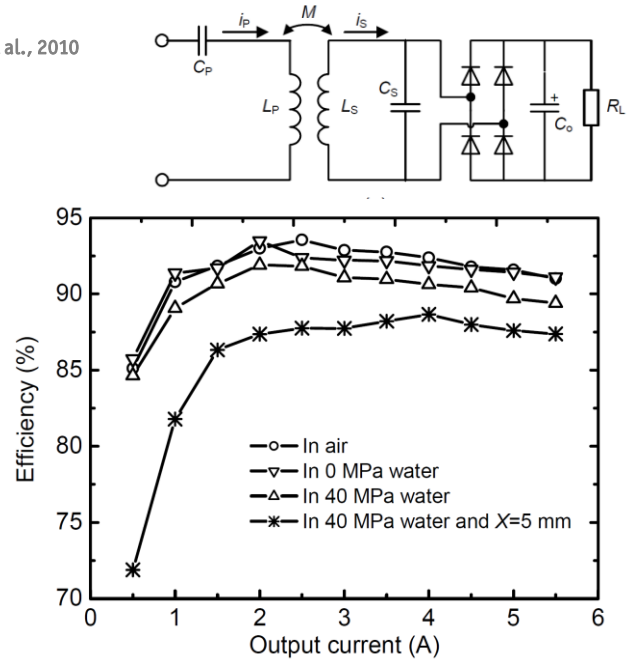
- Sensitive to Misalignment & Biofouling → Larger Airgap
- High Ambient Pressure → Reduced Core Permeability Due to Piezomagnetic Property of Ferrite
- Primary & Secondary Pads Need to be Matched in Shape & Size → Limited Interoperability

Wireless AUV Charging — Split-Core Transformers – 2/2

- "Wet-Mate"- Connectors / Direct El. Contact Replaced by Split-Core Transformers → Higher Reliability
- Inductive Coupling Used for Power Transfer & Communication



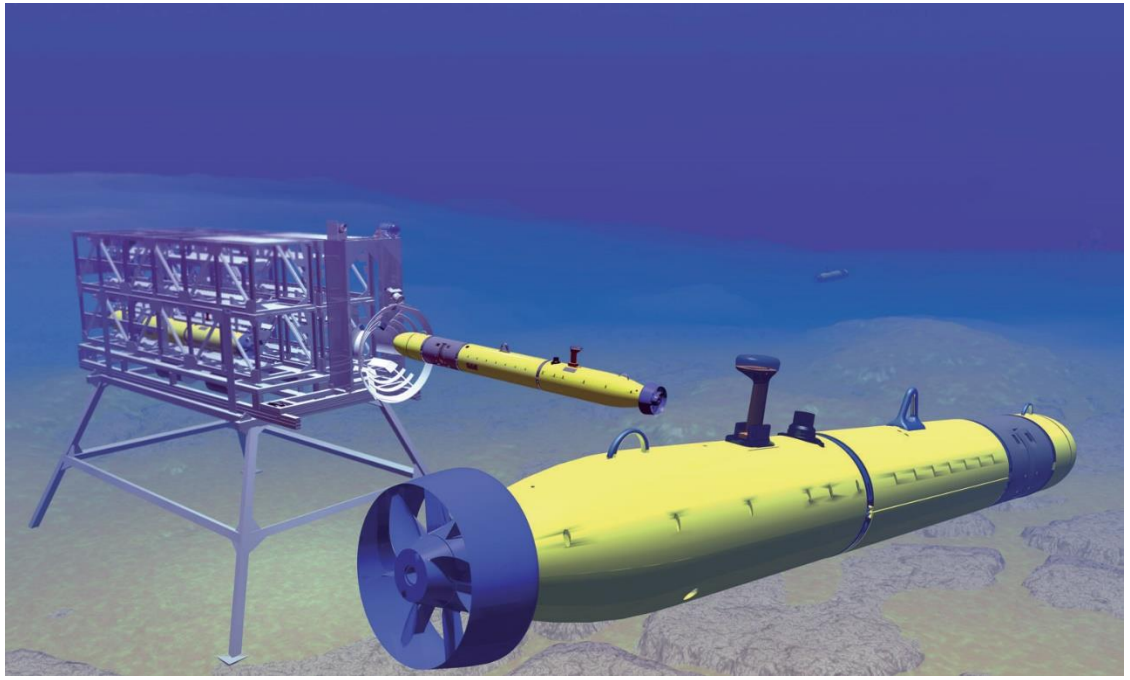
Source: Ze-song Li et al., 2010



- Pot Core (D = 48mm) / 2 mm Airgap / Litz Wire Wdg / f = 94 kHz | Elastic Retention Claws & Guiding Leaves
- 400 W / η = 87... 90% Tested @ 40 MPa Water Pressure (4000 m) / X = 5 mm Non-Coaxial Positioning

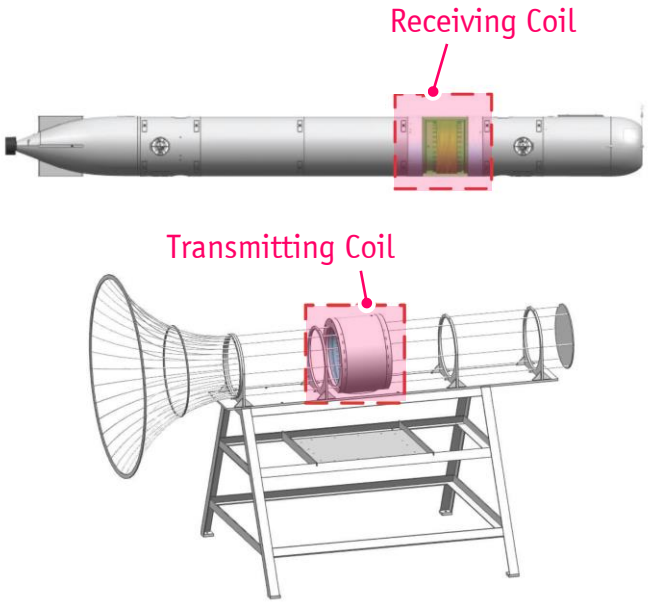
Wireless AUV Charging — Resonant IPT – 1/2

- Co-Axial Arrangement of High-Q Coils Operating in Resonance / Relatively Large Misalignment Tolerance
- Funnel-Shaped Recovery Cage — Entry Cone & Docking Tube



Source: www.oedigital.com

Source: Peizhou Liu et al., 2022

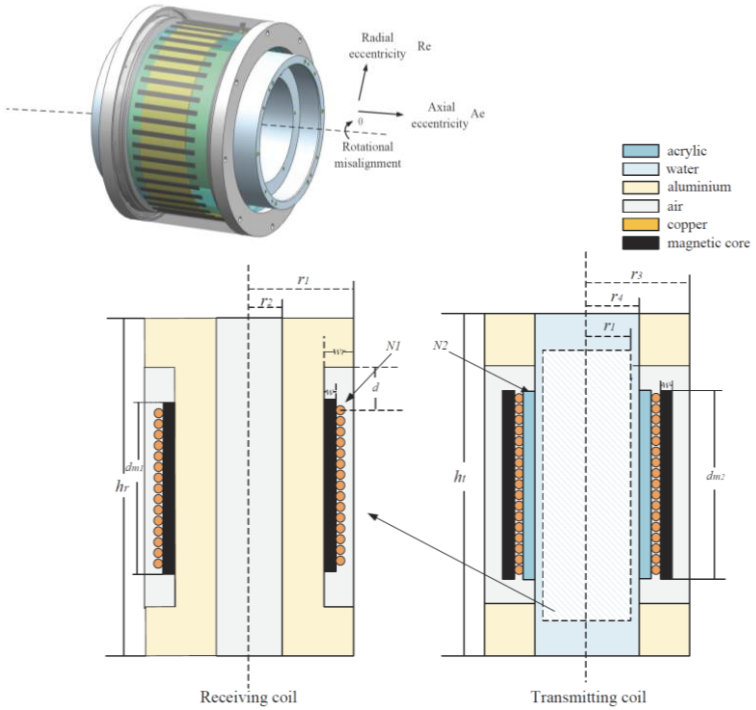


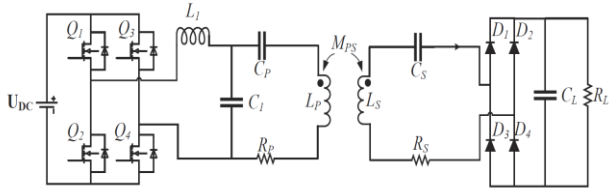
- Ferrite Elements for Magn. Flux Shaping → Red. Field / EMI Inside the AUV & Red. Eddy Currents in AUV Metal Hull
- Coil Geometry Adapted to Physical AUV Structure → Limited Interoperability

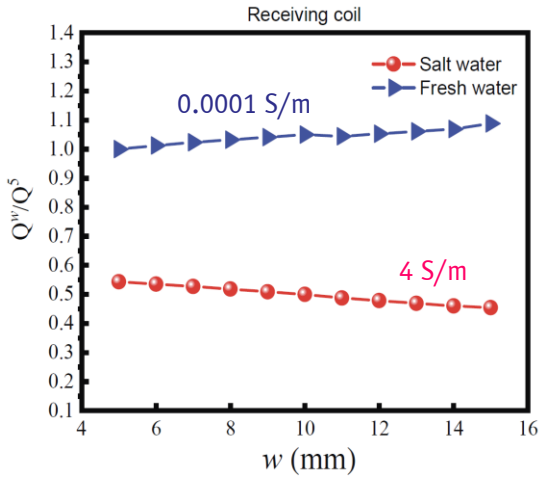
Wireless AUV Charging — Resonant IPT – 2/2

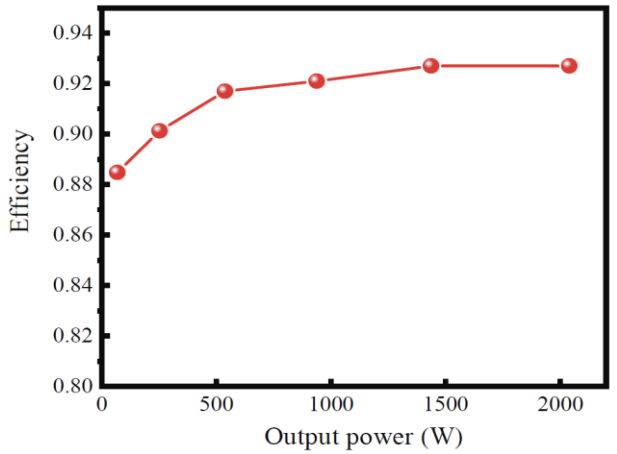
- Co-Axial Arrangement of High-Q Coils Operating in Resonance / Relatively Large Misalignment Tolerance
- Hydrodynamic AUV Hull Properties Unchanged

Source: Peizhou Liu et al., 2022









- LCC-S-Comp., f =200kHz, Litz Wire Wdg., w =5mm Magn. Layer Thickness, r_3=22.5cm, h_t=30cm, r_1=16.2cm, h_r=20cm

Wireless AUV Charging — Biofouling

- Accumulation of Marine Microorganisms on Wetted Surfaces → Misalignments & Larger Airgaps
- Prevention by Copper-Based Anti-Foul Painting & Heating to Biocidal Level Killing Off Microbes

Source: J. Oiler et al., 2015

- Study on WPT Coils, D=12.5cm, 45 Days Immersed in San Diego Bay (Unheated), w/ & w/o Anti-Foul

Industrial Subsea AUV Charging System

Industrial Subsea AUV Charging System – 1/3

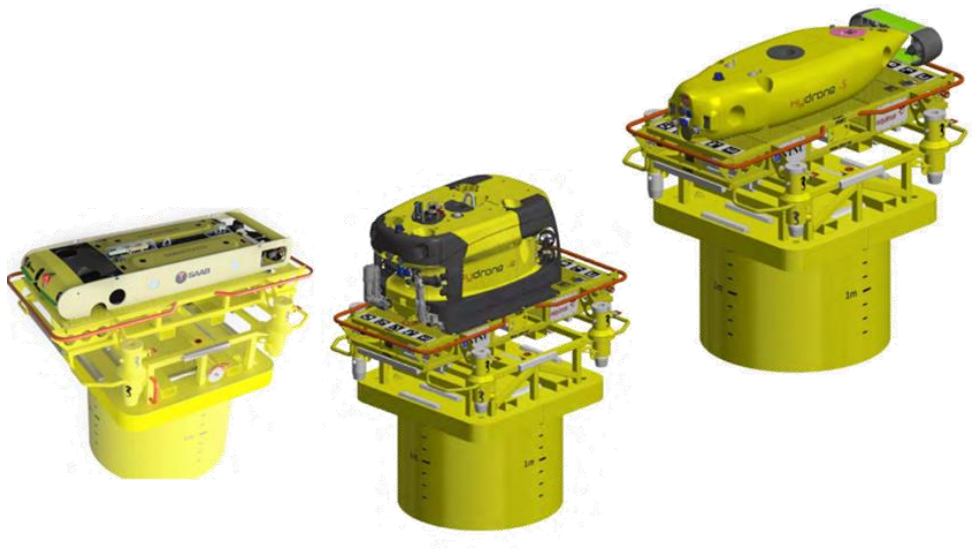
- "Universal" Open-Standard Docking Station — Interoperability with AUVs of Different Makes / Shapes / Sizes
- 2.5kW @ 95% Efficiency Inductive Power Transfer / 3000m Operation Depth / 15 Years Lifetime

Source: UNPLUGGED SUBSEA USB SUBSEA INDUCTIVE SOLUTIONS

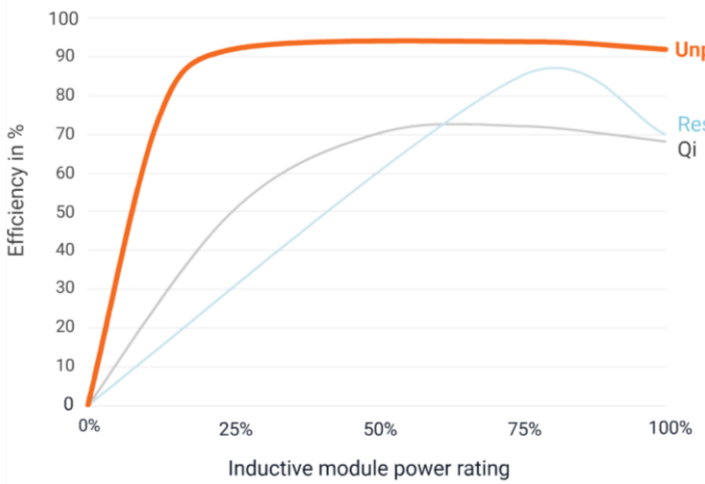
- Homing Mode / Primary Side of Inductive Connector Activated During Vehicle Approach
- Drone Utilizes Magnetic Field for Precise Docking

Industrial Subsea AUV Charging System – 2/3

- "Universal" Open-Standard Docking Station — Interoperability with AUVs of Different Makes / Shapes / Sizes
- 2.5kW @ 95% Efficiency Inductive Power Transfer / 3000m Operation Depth / 15 Years Lifetime



Source: UNPLUGGED SUBSEA USB SUBSEA INDUCTIVE SOLUTIONS



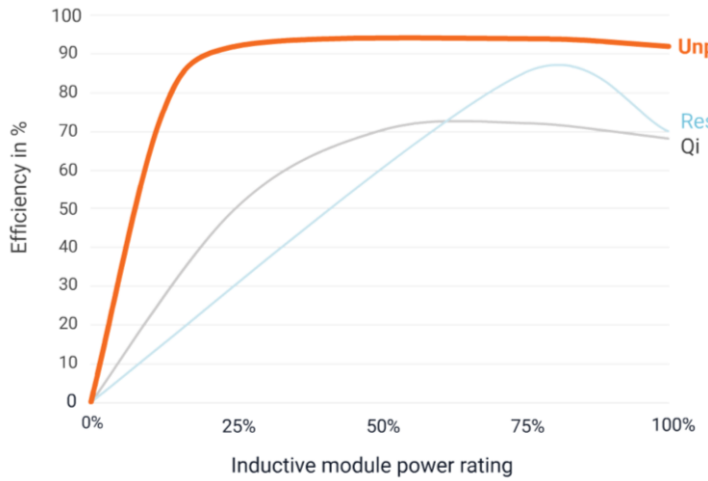
25x25x10cm / 3kW

- Homing Mode / Primary Side of Inductive Connector Activated During Vehicle Approach
- Drone Utilizes Magnetic Field for Precise Docking

Industrial Subsea AUV Charging System – 3/3

- "Universal" Open-Standard Docking Station — Interoperability with AUVs of Different Makes / Shapes / Sizes
- 2.5kW @ 95% Efficiency Inductive Power Transfer / 3000m Operation Depth / 15 Years Lifetime

Source: UNPLUGGED SUBSEA USB SUBSEA INDUCTIVE SOLUTIONS



25x25x10cm / 3kW

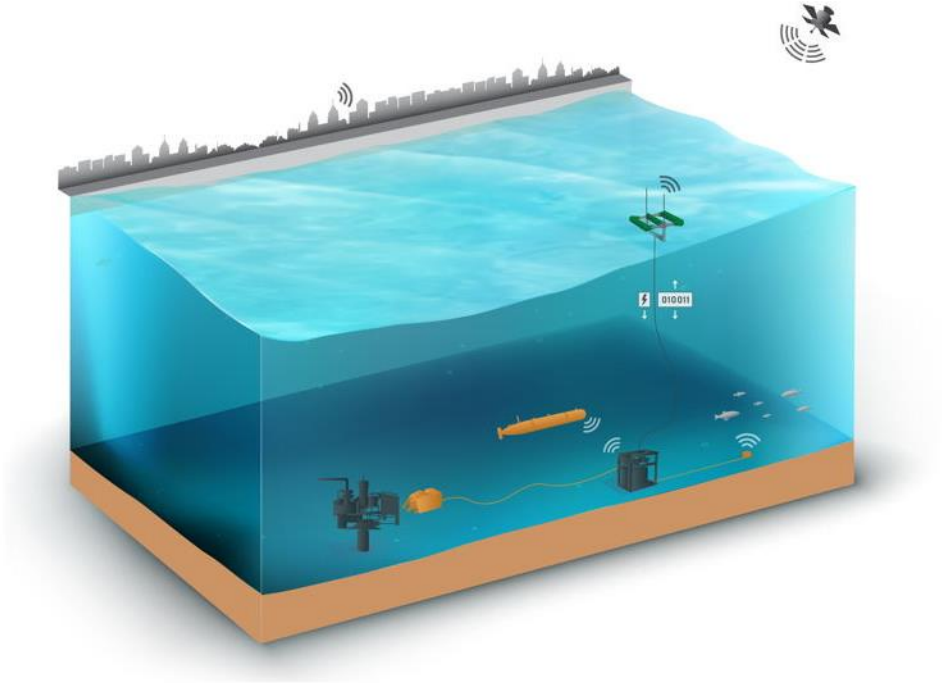
- Homing Mode / Primary Side of Inductive Connector Activated During Vehicle Approach
- Drone Utilizes Magnetic Field for Precise Docking

Local Power Generation for AUV Charging Stations

Local Power Generation for AUV Charging Systems

- Local Power Generation Using Surface Wave Energy | Wind Energy Converter
- Single Combined Mooring / Data / Communications | MV Power Supply Cable (3 kV, 3000m)
- 2-Way Satellite Communication with On-Shore Control Center via Surface Antenna

Source: C-POWER



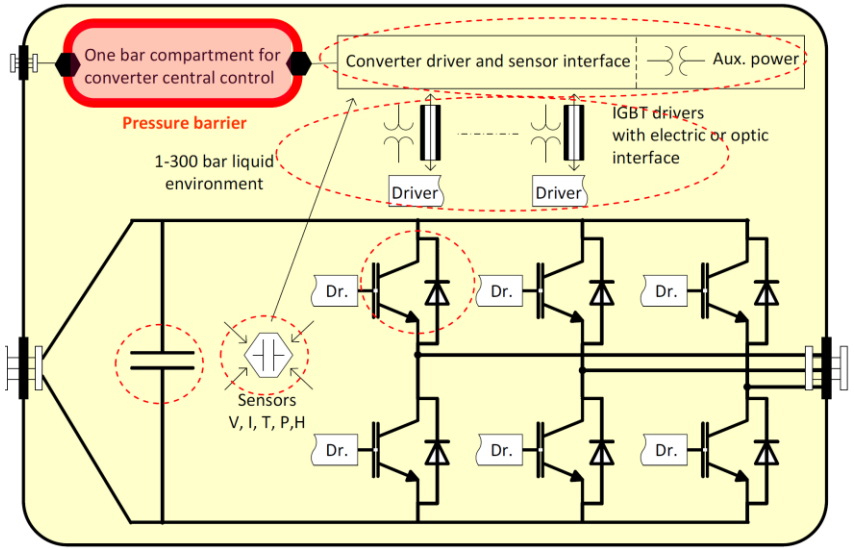
Source: OPT OCEAN POWER TECHNOLOGIES

- Battery Backup Integrated Into Seafloor Base-Unit OR Into Wave Energy Harnessing "Power Buoy"

Remark Electronics Pressure Housings

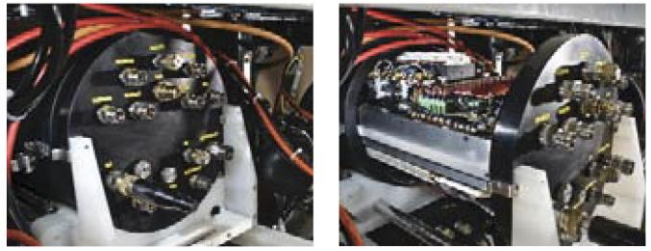
- Air or Gas Filled Components → Would Implode in Large Depths (e.g. 6000 m → 600 bar)
- One-Atmosphere Housings → Maintain Constant Inside Pressure / Cylindrical or Spherical Shape
- Pressure Balanced Housings → Int. ≈ Ext. Pressure / Oil Filled – No Voids / Not Shape (Cooling) Restricted !

Source: M. Hernes SINTEF



Source: SAAB

Electronics Compartment of Seaeye Jaguar

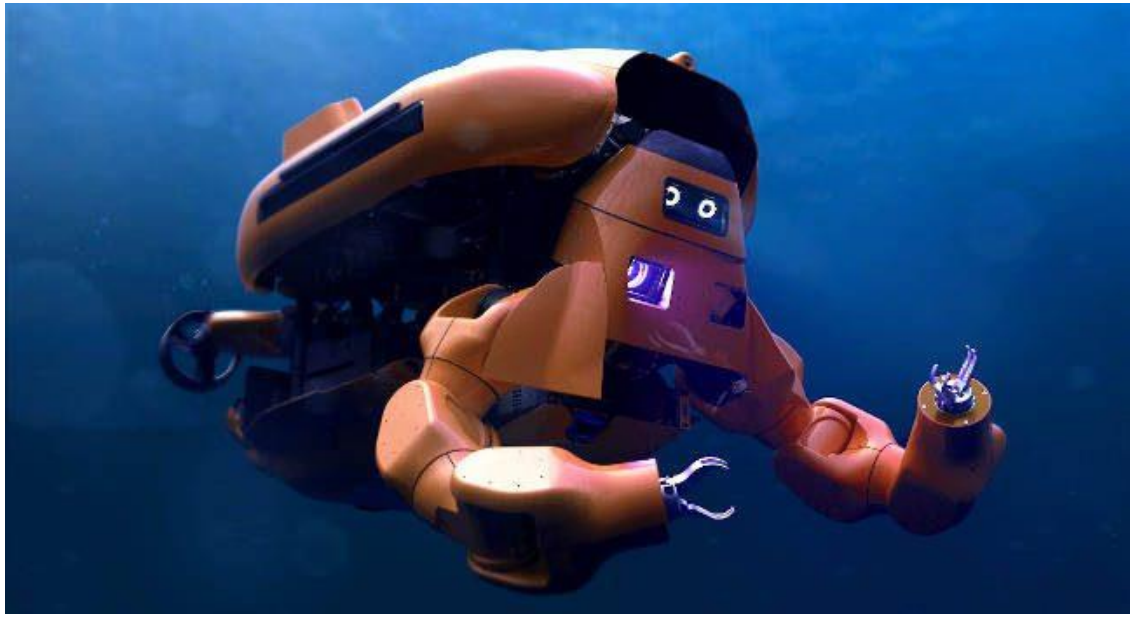


- Research on Pressure-Tolerant Power Electronic Components (300 bar) @ SINTEF
- IGBTs → Sw. Behavior Unaffected / Chip Interface Needs to be Protected from Surrounding Liquid
- Pressure Affects BH-Curve of Magnetic Cores & Impairs Self-Healing of PP Film Cap. → Voltage Derating

Outlook

Autonomous Shape-Shifting Submarine Robots / "Aquanaut"

- Long Range All-Electric AUV → Un-Tethered Humanoid ROV with Two 8-Axis Arms
- Travels in Hydrodynamic Submarine Form to Deep Water Destination & Transforms Into ROV

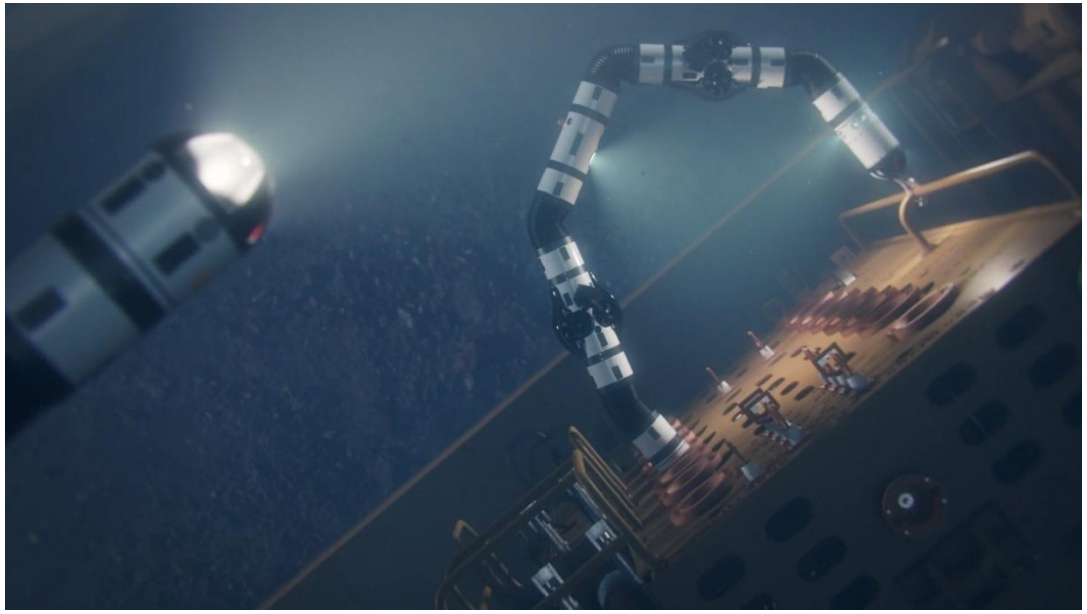


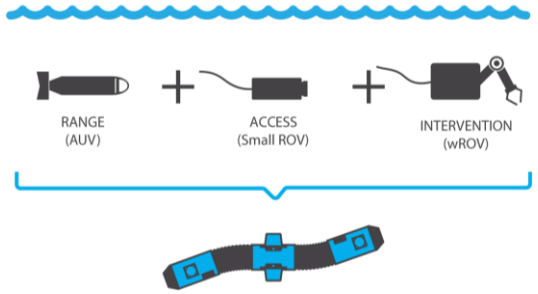
Source: HOUSTON MECHATRONICS

- Designed for Maintenance of Deep Water Oil & Gas Wells / Pipelines
- Semi-Autonomous Operation — Small Unmanned Surface Vessel Relays Signals to Communication Satellites

Snake-Like AUV / Eelume

- Self-Propelled Autonomous Modular Flexible Robotic Arm → IMR in Confined Spaces
- Slender Body for Straightened Joints → Allows Transitions Over Long Distances / Survey AUV
- Thruster | Joints | Sensor | Payload Modules → Adaption to IMR Task / "Dual-Arm" for U-Shaped Body
- Subsea Docking Station for Battery Charging / Data Transfer / Assignments



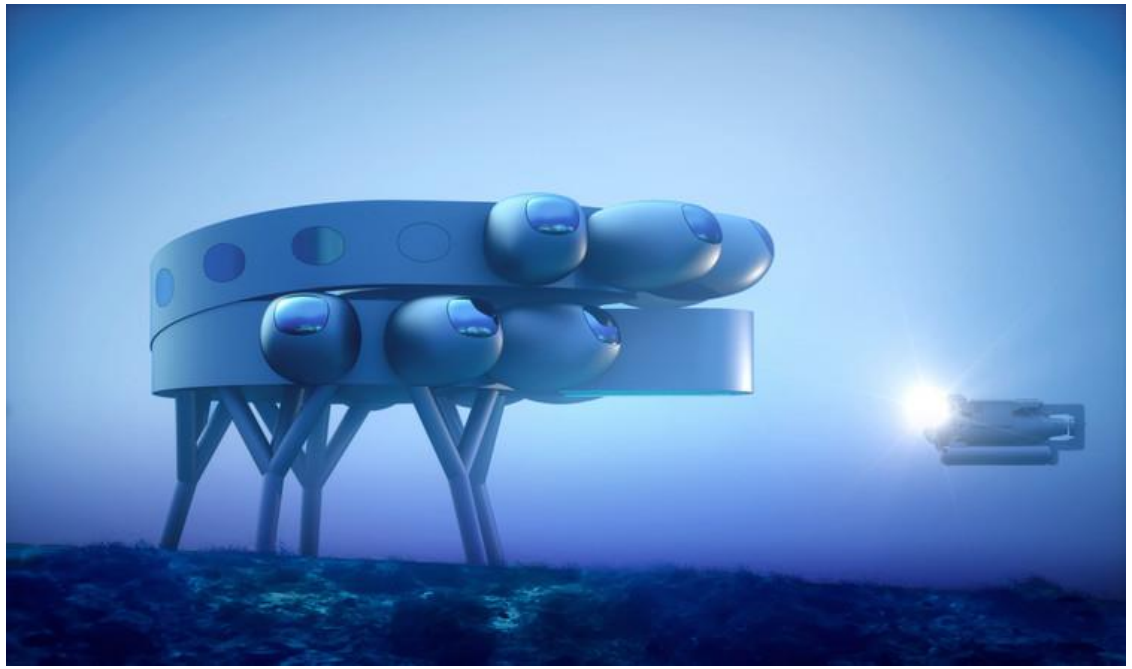


Source: https://eelume.com

- Eelume — Equinor / Kongsberg Maritim / NTNU

Future Underwater Stations

- Underwater Version of the International Space Station
- Discovery of New Species of Marine Life / Aquacultures / Understanding Climate Change Effects



Source: ArchDaily / Protheus

- PROTEUS — First in a Network of Future Underwater Habitats

Thank you!