Autonomy in the Maritime Domain – A System Perspective

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Definitions

Automatic

- the ability of a system to automatically carry out processes or perform actions
- does not make choices for itself – follows a script where the choice out of all possible courses of action have already been made
- if it encounters the unexpected it cannot adapt and waits for human help

➢ for an automated system, choices have been made or encoded, or are made externally

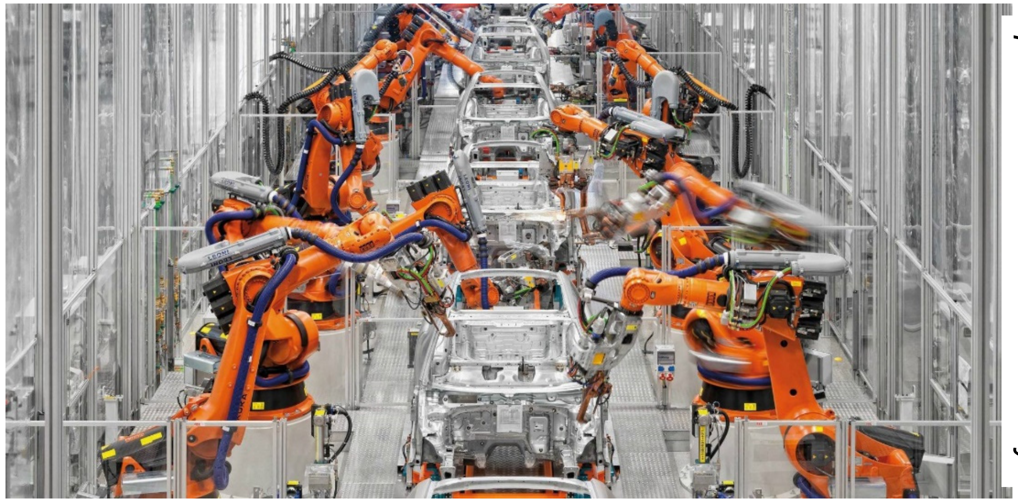


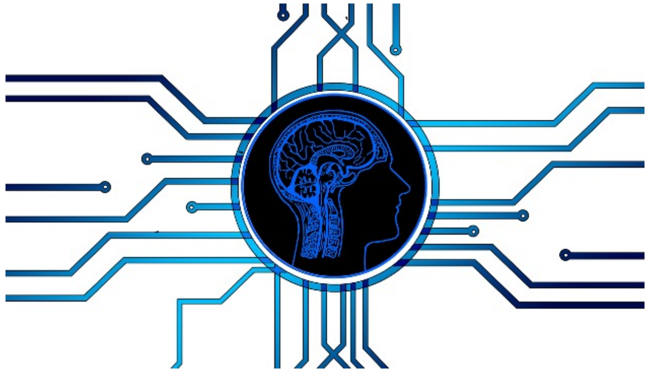
photo credit: Callum Bentley

Definitions

Autonomy

- ability of a system to govern itself by making decisions, implement / action the decision and check the effectiveness of the actions taken

- an autonomous system / robot makes choices of its own
  - tries to accomplish its objectives, without human intervention, even when encountering uncertainty or unanticipated events

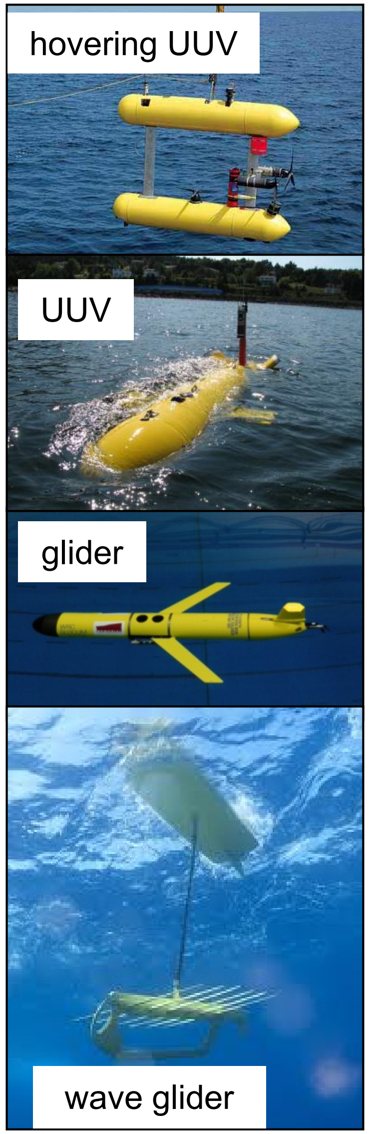


➢ in the context of autonomous systems, autonomy is the ability to make choices, enforce decisions by applying actions, evaluate results and adapt

Autonomous Maritime Systems

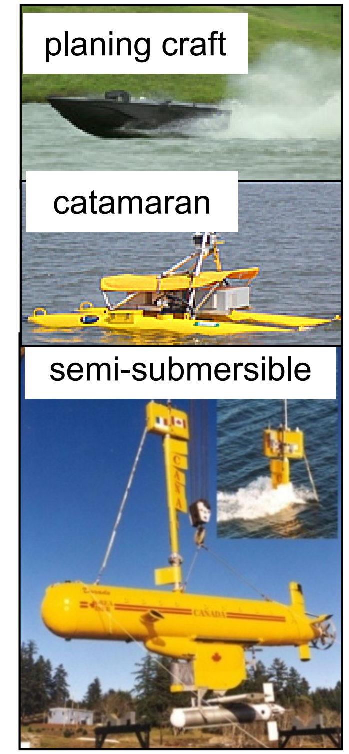
Deploying Marine Sensors on Autonomous Systems

UUV



- unmanned underwater vehicles (UUV)
  - free-swimming & powered by batteries
  - hover, flyby, sawtooth profile, skim surface (1 – 4 kt)
  - *bring the sonar to any point in the water column*
    - sonar positioning error not easily bounded
- unmanned surface vehicles (USV)
  - displaces water at rest; continuous GPS
  - high transmission bandwidth, e.g., planing craft, catamaran, semi-submersible, hovercraft (5−30 kt)
  - *deploy sonar only from high in the water column*
    - *sonar positioning error is bounded*
- unmanned aerial vehicles (UAV)

USV



UAV

Marine Autonomy – Outcomes

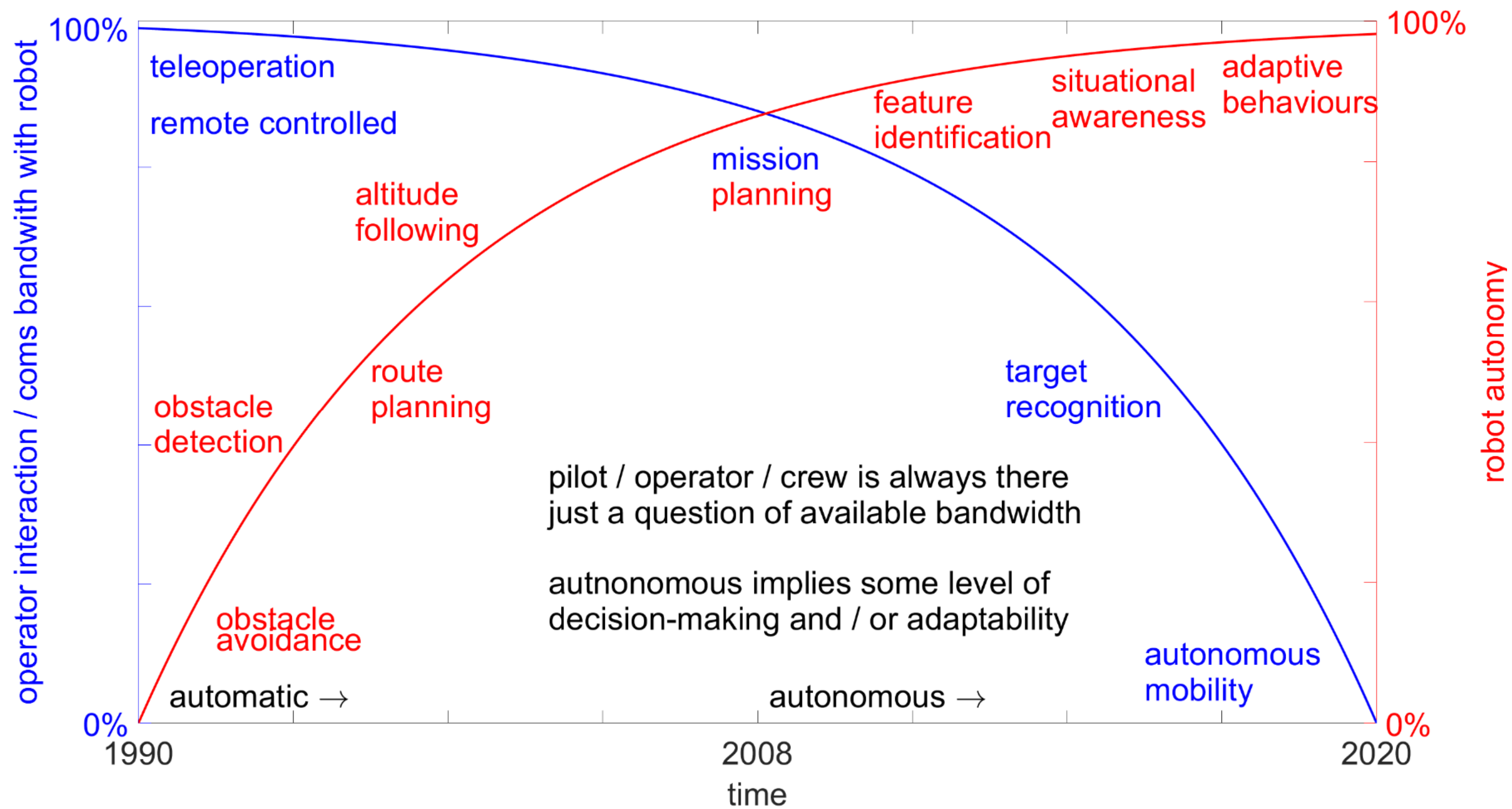
- until recently marine autonomous systems executed *scripted missions* (automatic)
- realize full potential of marine robots by conferring *autonomy* to adapt to dynamic ocean environment – scripted missions are inadequate for complex environments!
- ability for marine robots to autonomously:
  - reason, learn
  - make decisions
  - re-plan missions
  - adapt mission based on sensor measurement analysis / robot changes
  - collaborate with other robots and systems (manned or unmanned)
  - adapt to dynamic ocean environment, change in themselves, etc.

Autonomous System Capabilities

Maritime Motivation

- less human interaction
- overcome coms challenges
- dynamic environment
- manage workload

➢ compelling argument for maritime robot missions



State-of-the-Art Maritime Autonomy


USN UUV Master Plan (2004)

Example: Naval Mine Countermeasures (NMCM)

- naval mine counter-measures: persistence and reach
  - most est naval use of autonomous systems (c. 1990's Persian Gulf War)

mission:	search (detect)	classify	map (localize)	reacquire & ID	neutralize
UUV:	survey	MLO?	georeference	navigate to MLO	
operator:					analyze & decide

  - surveys, especially wide-area ones, can be performed autonomously
  - on-board analysis of sonar imagery to classify and georeference MLOs
  - replan mission to reacquire (re-image) MLO at high res and confirm its location

State-of-the-Art Maritime Autonomy

- NMCM is a fairly static mission
  - targets are not mobile or rapidly evolving
  - UUV payload sensor is the side scan / synthetic aperture sonar to deploy in-water
  - sensors, in situ analysis, coms, localization, decisions, etc. integrated into one system of systems – the UUV

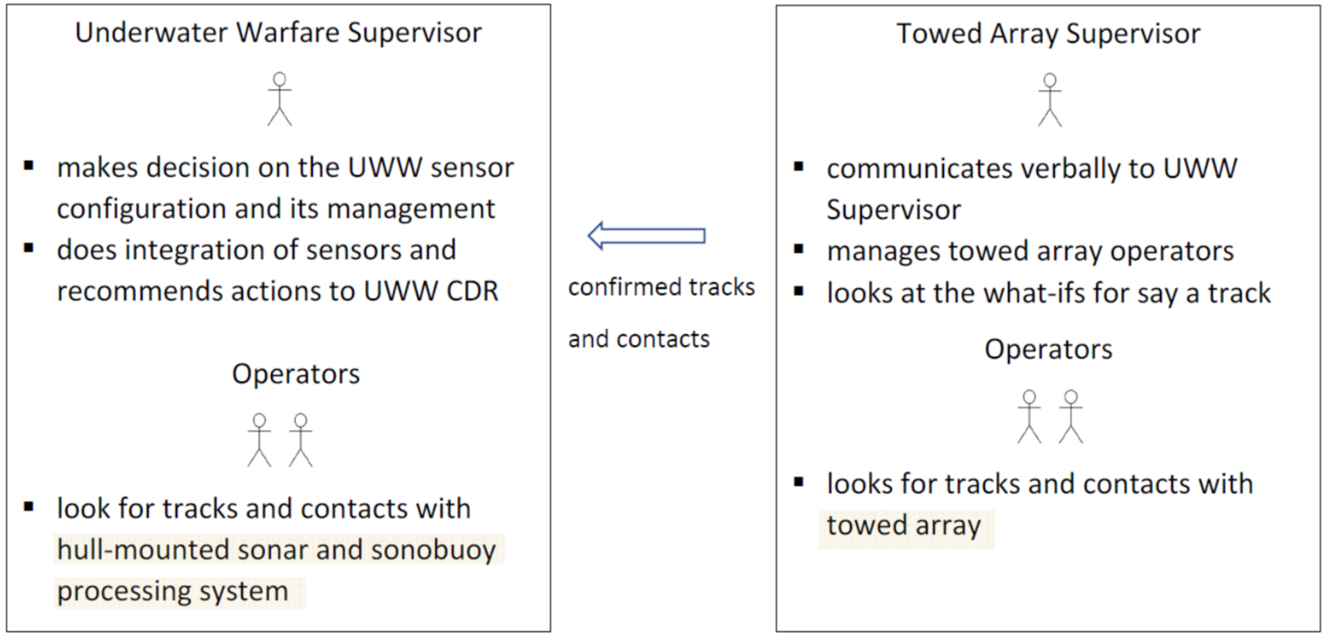
Royal Canadian Navy prepares to deploy on NMCM mission with a REMUS 100 UUV

- Anti-Submarine Warfare (ASW) is a much more dynamic mission
  - targets are mobile at high speeds and actively work to evade
  - higher tempo and multiple sensors deployed across multiple platform types
  - sensors, analysis, coms, and decisions not integrated into systems of systems

New Maritime Autonomy Requirements

Example: Anti-Submarine Warfare (ASW) – Sensors not Integrated ⇒ Challenges

- ASW uses manned platforms (ships, MPA, helos) with passive and active sonar:
- different OEM for each sensor and their sub-systems ⟹ lack of common tools
  - arrays
  - hull-mounted sonar
  - software
  - sonobuoys
  - Combat Management System



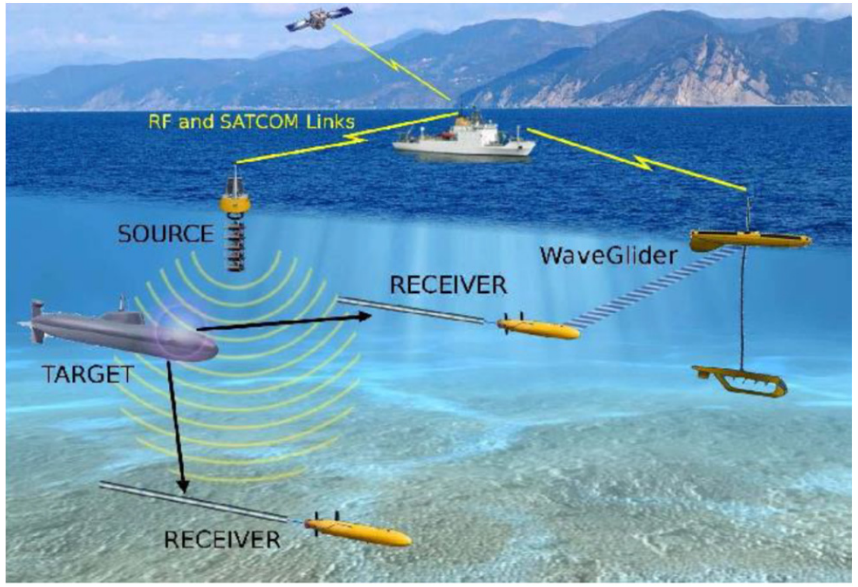
- mostly manually fuse these systems' measurements to localize and track mobile u/w targets ⇒ such stove-piped systems limit what is possible in the autonomy

➢ NMCM was at that point once – ASW sensor OEMs to design for UUVs and USV

New Maritime Autonomy Requirements

Example: Anti-Submarine Warfare (ASW)

- a concept with some gravitas is a distributed network of UUVs (1000's)
  - manned and unmanned sensors distributed from seabed to above-water and integrated into a system of systems



Distributed UUVs (source: CMRE) [1]

  - adversary overwhelmed by many small targets cf a naval group of a few surface vessels – expend ordinance to take out only an UUV at a time
  - UUVs collaborate to det target heading, speed, and position (sonobuoys, LBL)

New Maritime Autonomy Requirements

Example: Anti-Submarine Warfare

- USV or UAVs to adaptively sample with dipping sonars to passively localize an u/w mobile target in a wide-area search
  - such sonars designed for manned helicopter deployments

globalsecurity.org

AN/AQS -18 dipping sonar

- USV used as a relay / router (as in NMCM)
- manned assets like ships support UUV / USV / UAV operations
  - coordinate sensors and weapons
  - integrate intel from other sources
  - make decisions that have high consequences

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New Maritime Autonomy Requirements

Example: Anti-Submarine Warfare

- autonomy requirements for this vision above and beyond NMCM:

1. higher energy density on-board UUVs
2. on-board signal processing to interpret sensor measurements (beamforming)
3. persistence of in-water UUVs towing arrays
4. long range robust underwater acoustic coms for collaborative robots
5. how to address: uncertainty in sensor measurements and adversary intel, RoE, COLREGS, IMO International Law, doctrine, etc.

… challenges to overcome →

Emerging Maritime Autonomy

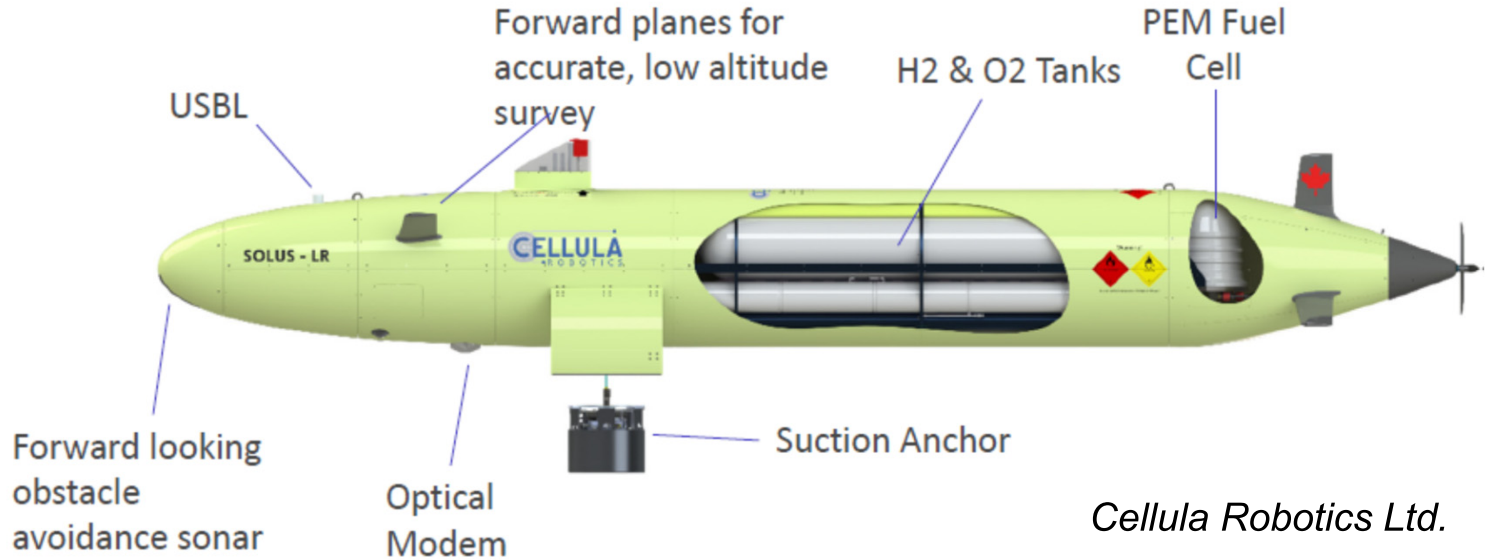
1. High Energy Density On-board UUV Sources

- given propulsion, vehicle sub-systems, payload sensor (tow) and autonomy computations of a free-swimming platform there is enormous demand for energy
  - lithium-ion batteries of high energy densities have limits
  - also volatile chemistry so difficult to transport commercially (use DND ships)

- fuel cells have emerged as an option for UUVs (e.g. Solus-LR)

  250 kWh of energy
  (1200 W continuous)

  3000 km range
  3000 m depth
  8.5 m length x 1 m dia

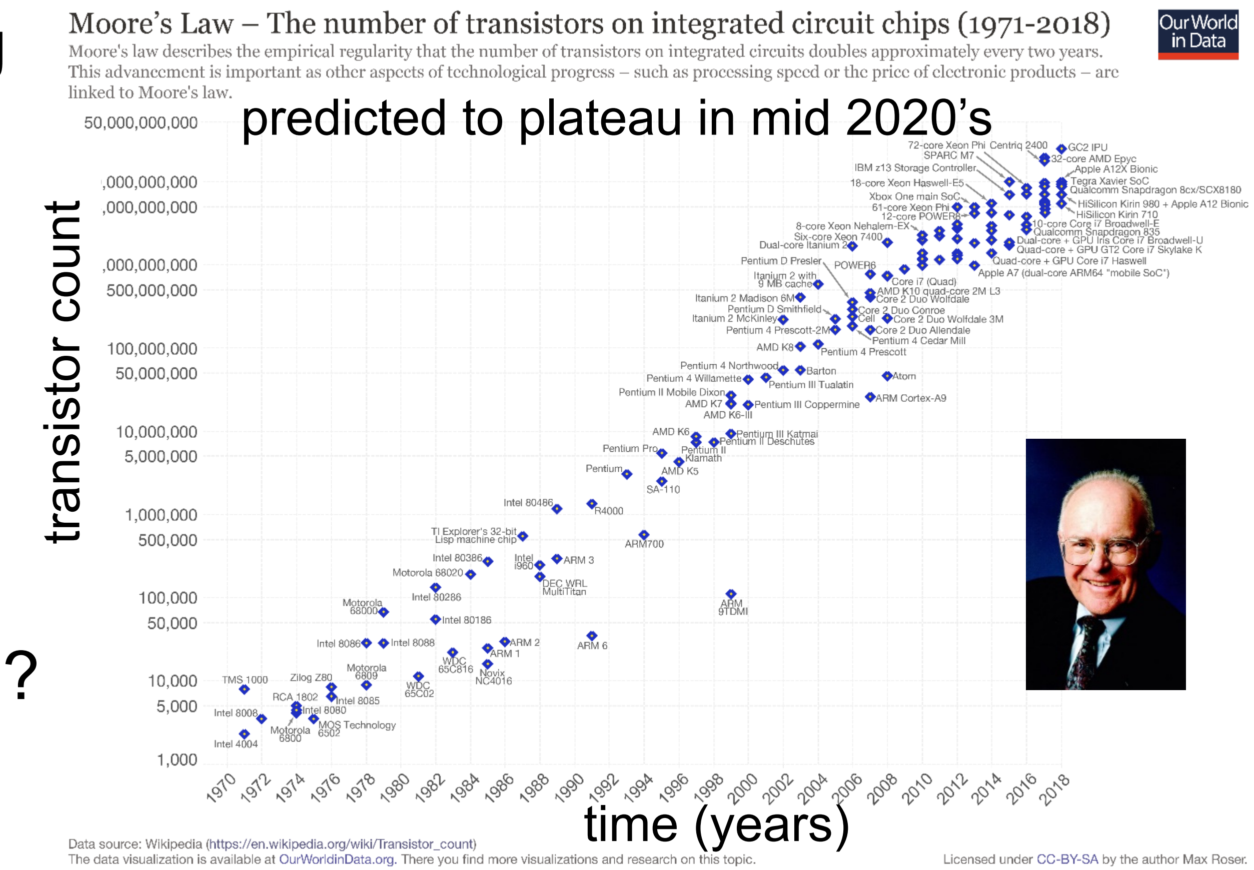


Cellula Robotics Ltd.

Emerging Maritime Autonomy

2. On-board Signal Processing to Interpret Sensor Measurements

- on-board fuel cells means more processing
  - beam-forming on-board the UUV?

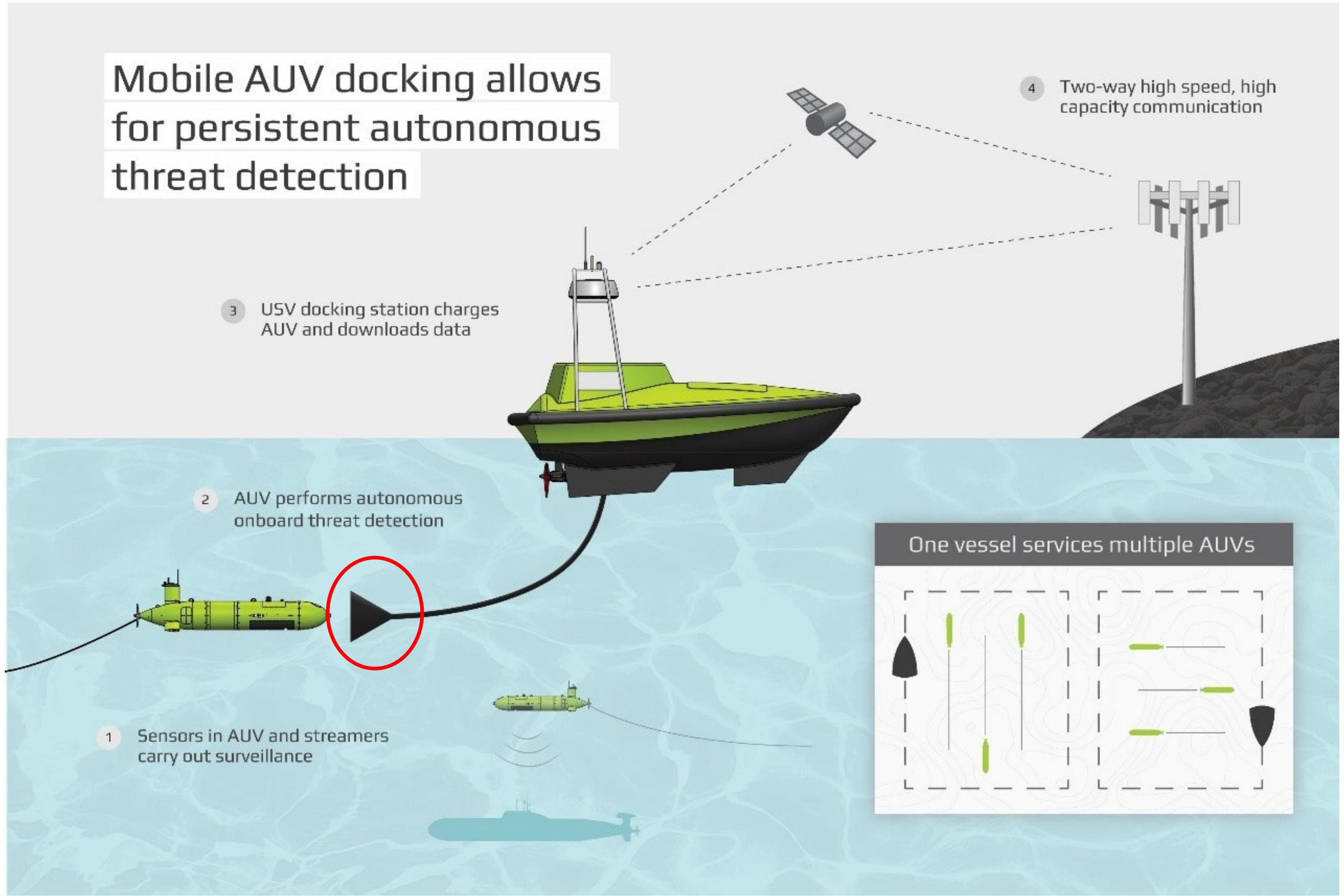


- Moore's Law projected 10 yr forward would not produce sufficient on-board processing in UUV form factor
  - transforming shift – quantum computing?

- in situ training and implementation of on-board machine learning models
  - increasingly powerful GPU computers

Emerging Maritime Autonomy

3. Persistence of In-Water UUVs Towing Arrays



- novel underway docking station
  - ML det UUV pose rel dock
- UUV downloads its data and is charged while underway
  - array maintains its (safe) underway profile
- collaboration of UUV, USV and UAV for persistent surveillance
- operate as an unattended system in the Canadian Arctic

Emerging Maritime Autonomy

4. Long Range Robust Underwater Acoustic Coms – Departure from Above-Water

- challenges in remote sensing, wireless communications and localization
  - best sensing and communications modality is acoustics
- frequency and range dependent attenuation
  - ranges are low by comparison to above-water
- poor bandwidth
  - low carrier frequencies (10's of kHz) by comparison to above-water
- no universal positioning system in featureless (or over-cluttered) environments
  - mostly reliant on aided inertial navigation and localization methods

Emerging Maritime Autonomy

4. Long Range Robust Underwater Acoustic Coms – Departure from Above-Water

- if many UUVs are distributed in a network there is a requirement to communicate over much longer distances and with greater bandwidth than presently common

- how to overcome the communications challenges?

- underwater software-defined modems / radios for coms
  - more adaptive to the temperamental underwater acoustic channel
  - full-duplex communications underwater
  - increase bandwidth $> 2 \times$

- satellite communications protocol specification (SCPS)

Subnero Ltd.

5. Uncertainty in Sensing and Intel – Sensors with Uncertainty Informing Decisions

- underwater ambient is high
- water temperatures increasingly warmer
- fluctuations over wide range of temporal and spatial scales – global → local episodic events

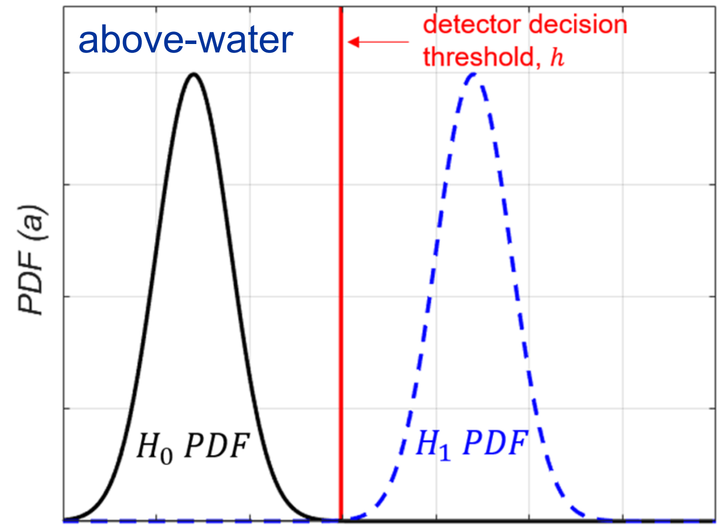
➢ ∴ SNR poor by comparison to above-water

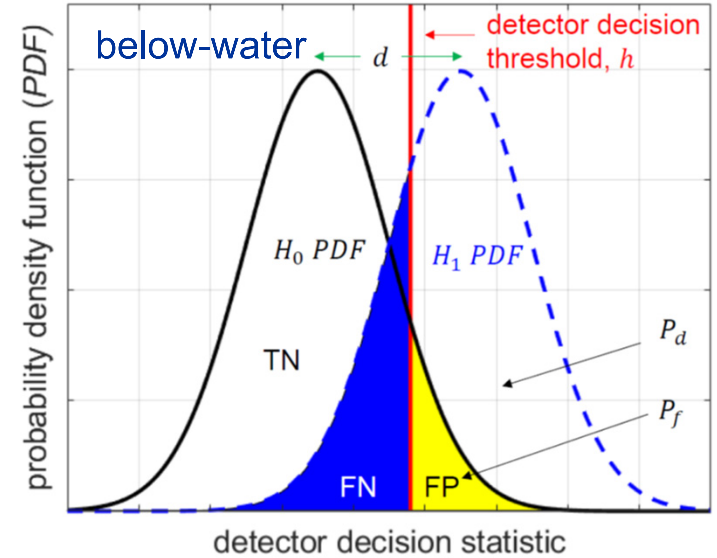
		at receiver input [ground truth]	
		signal-present, H_1 Positive	noise-only, H_0 Negative
decision	signal-present Positive	correct detection P_D **[TP]**	false alarm P_f **[FP]**
	noise-only Negative	missed detection $P_m = 1 - P_D$ **[FN]**	null decision $1 - P_f$ **[TN]**

- stochastic approaches for decisions based on in-water sensor measurements
  - detection SNR is not high ⇒ high FP and FN rates
    - absolutely need confidence when consequences are based on such decisions

5. Uncertainty in Sensing and Intel – Sensors with Uncertainty Informing Decisions

- given poor SNR underwater
  - ∴ classifications and reacquisitions may also be poor
    - difficult to automate under such conditions
  - – a mistake like sinking a vessel or misidentifying an entity as friendly has severe consequences
- processing for correlation and identification is complex so an operator is needed for high level of confidence before a track is engageable
- operator-on-the-loop also provides oversight for systems that can be automated or autonomous





Emerging Maritime Autonomy

5. Uncertainty in Sensing and Intel – Operator-on-the-Loop Part of Autonomy System

- operators' training and experience allows them to assemble an overall picture to confidently say "this, is a target"

payload sensor + robot + other systems

only an operator can provide this

– data ⟹ information ⟹ knowledge

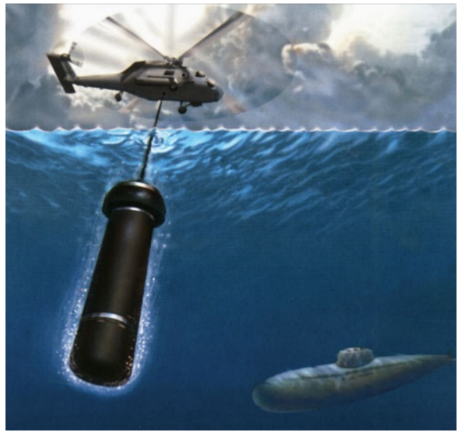
[raw numbers] ⟹ [numbers processed with some context] ⟹ [context, experience, beliefs, perspective]

– data and information integration can happen over a long time period to classify
  - imperfect information: may draw on a database of limited signatures
    adversary actively shifting their actions and tactics

➢ when large Δ in knowledge and large σ in sensing (ASW) ⟹ operator knowledge is a *vital* autonomy system component

Emerging Maritime Autonomy

5. Uncertainty in Sensing and Intel – Layered System of Systems



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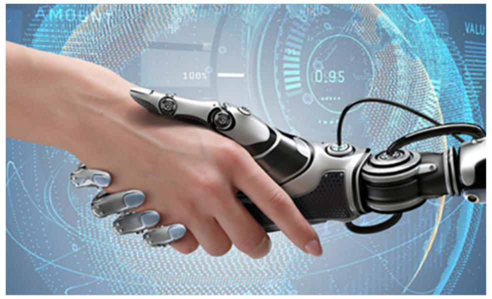
AN/AQS -18 dipping sonar

- UAV / USV with dipping sonars to autonomously sampling to passively localize an u/w mobile target in a wide-area search
  - operator should only need to monitor this
- when a threshold number of positive fixes are acquired and the autonomous 'fleet' is in agreement there may be a target, the operator takes over
  - directs the autonomous dipping sonars' mission



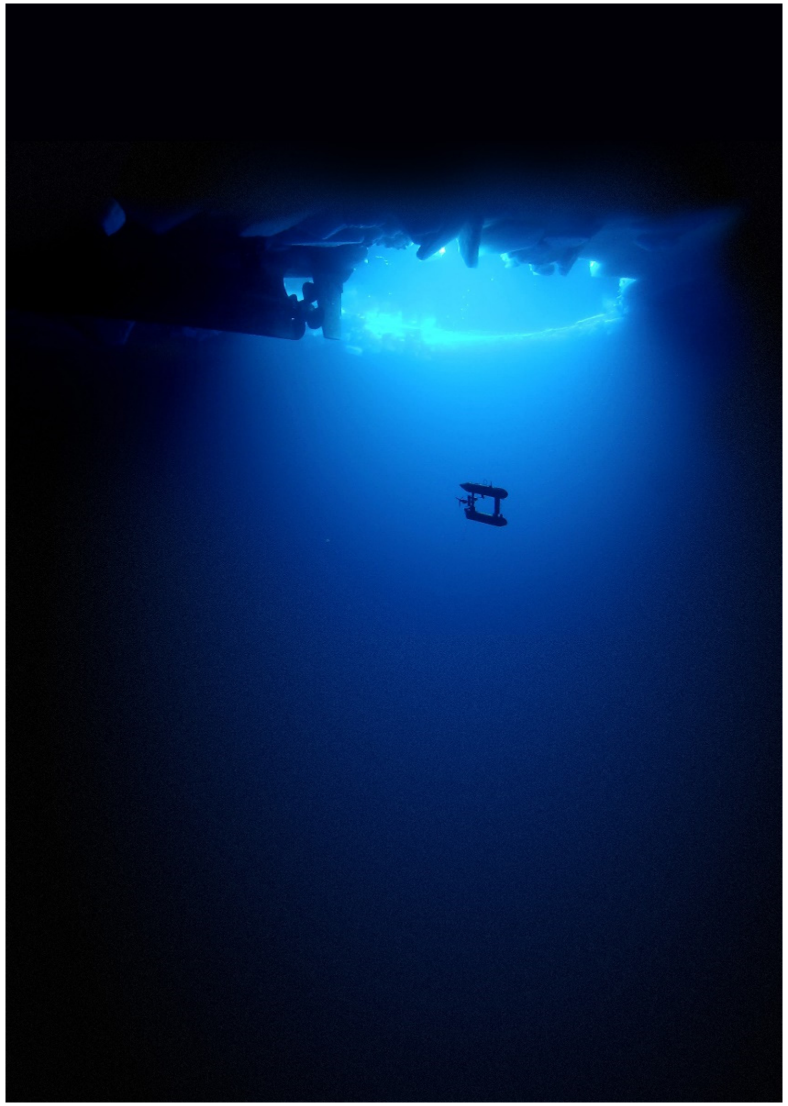
https://www.mdis.edu.sg/blog/man-and-machine-can-they-co-exist/

- higher operator involvement may make it tactical and the posture changes
- when the target appears to be well out of range the autonomous fleet could revert to autonomous adaptive sampling again

Concluding Remarks

- harsh underwater environment for sensing, communications and localization makes maritime autonomy different from above-water autonomy

- complex maritime missions like ASW should have an operator-on-the-loop:
  - operator knowledge is a vital component of the autonomy system of systems
  - also provides oversight for autonomous tasks like surveys, sampling, etc. – autonomy aids operator



Credit: Klaus Meiners WHOI

SeaBED AUV mapping of ice thicknesses.

Questions?

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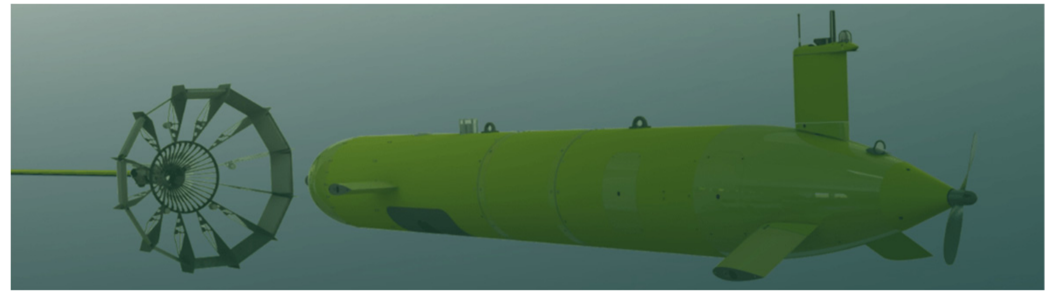

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Explorer UUV approaches underway dock to re-charge batteries and download data while remaining underway like it would have to if it was towing an array.

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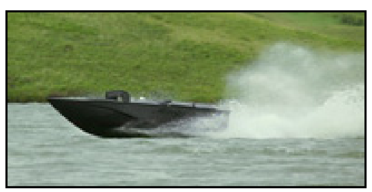




References

[1] Alleslev, L., NATO Parliamentary Assembly, Science and Technology Committee, “NATO Anti-Submarine Warfare: Rebuilding Capability, Preparing for the Future,” Special Report, October 2019, 23 pg.