

The Maritime Journey Towards Autonomy

A Model-Based System Engineering Approach

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Version 1

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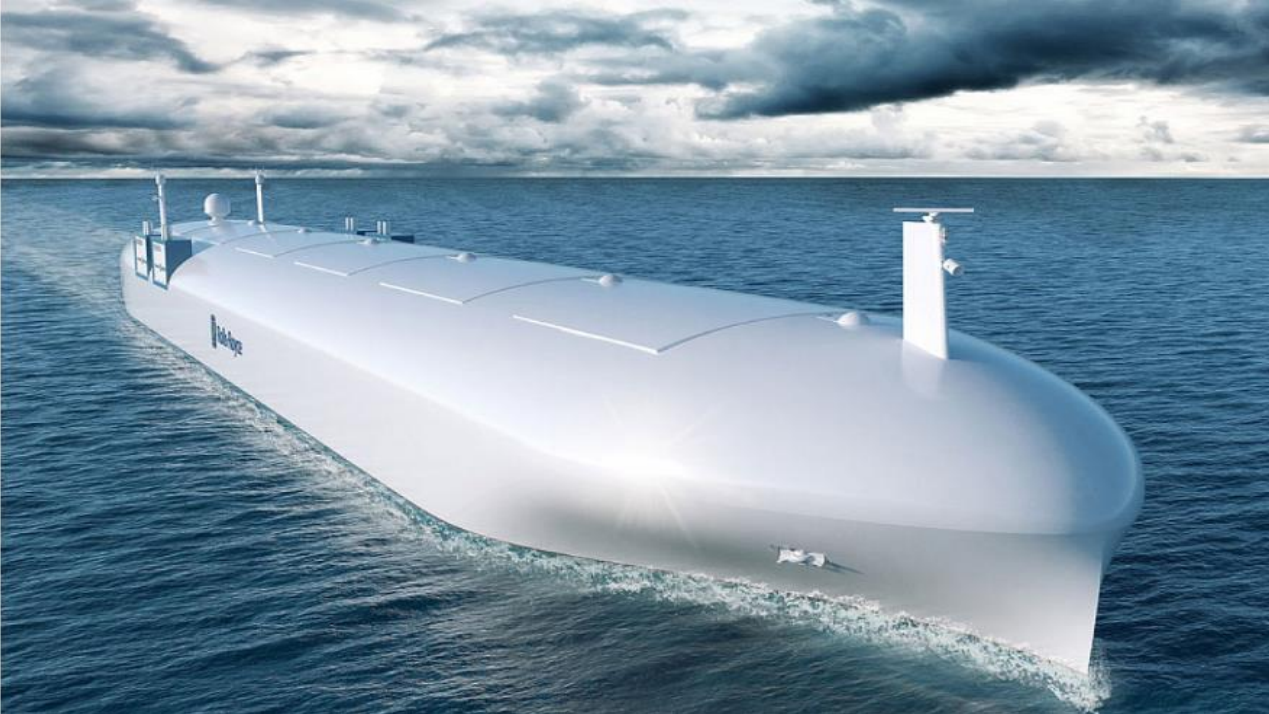
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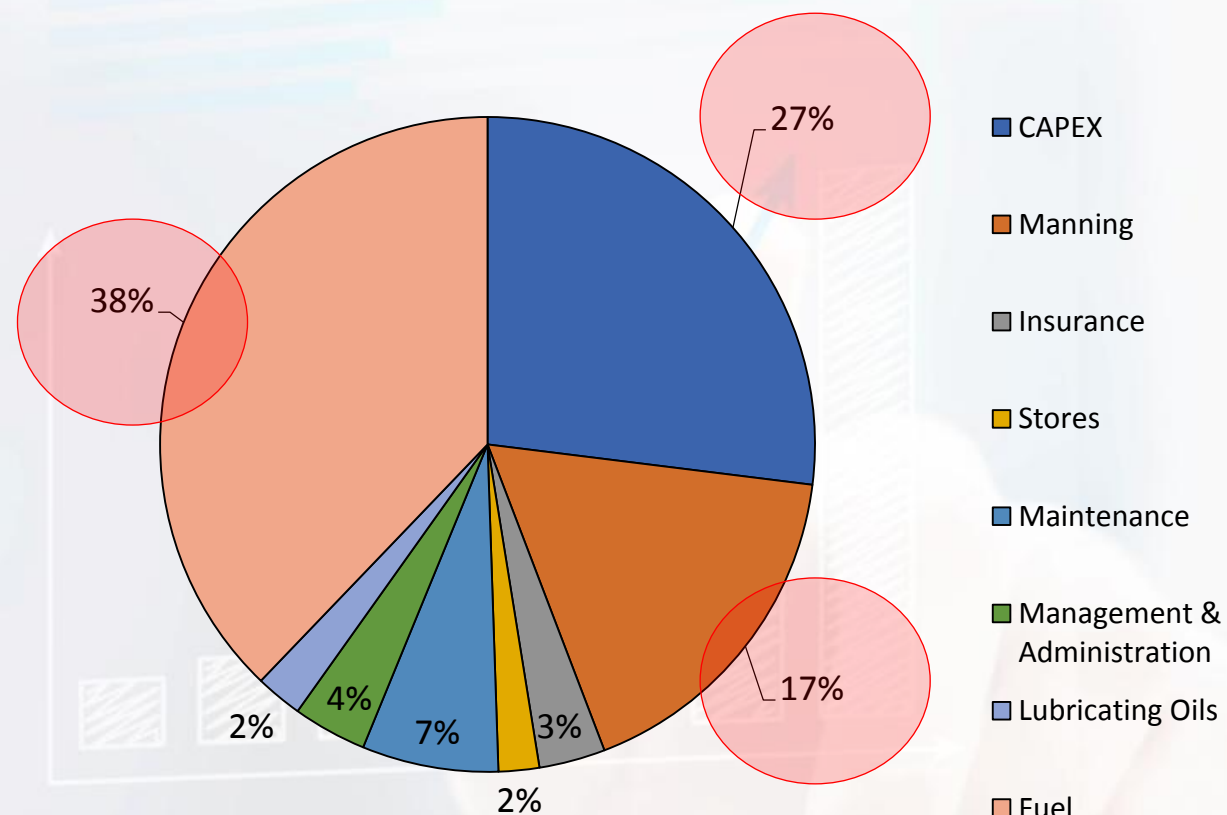
Contents

- Journey towards Autonomy - Maritime Vision
- Key Engineering & System Engineering principles for autonomous infrastructure
- Challenges:
 - Understanding the “Product” – System of Interest (SoS, Enabling & Interoperating Systems)
 - Define Future products (Autonomy)
- How Autonomous is the System?
- Lesson learned - Autonomy Framework from other sectors
- Proposed Maritime Autonomy Framework (MAF)
 - The interpretation of level of autonomy
 - The attributes of an effective maritime autonomy framework
 - The integration of MAF & Enterprise Framework
- A Model-Based System Engineering Approach
- Key Take Away



Why R&A Vessels - Cost structure

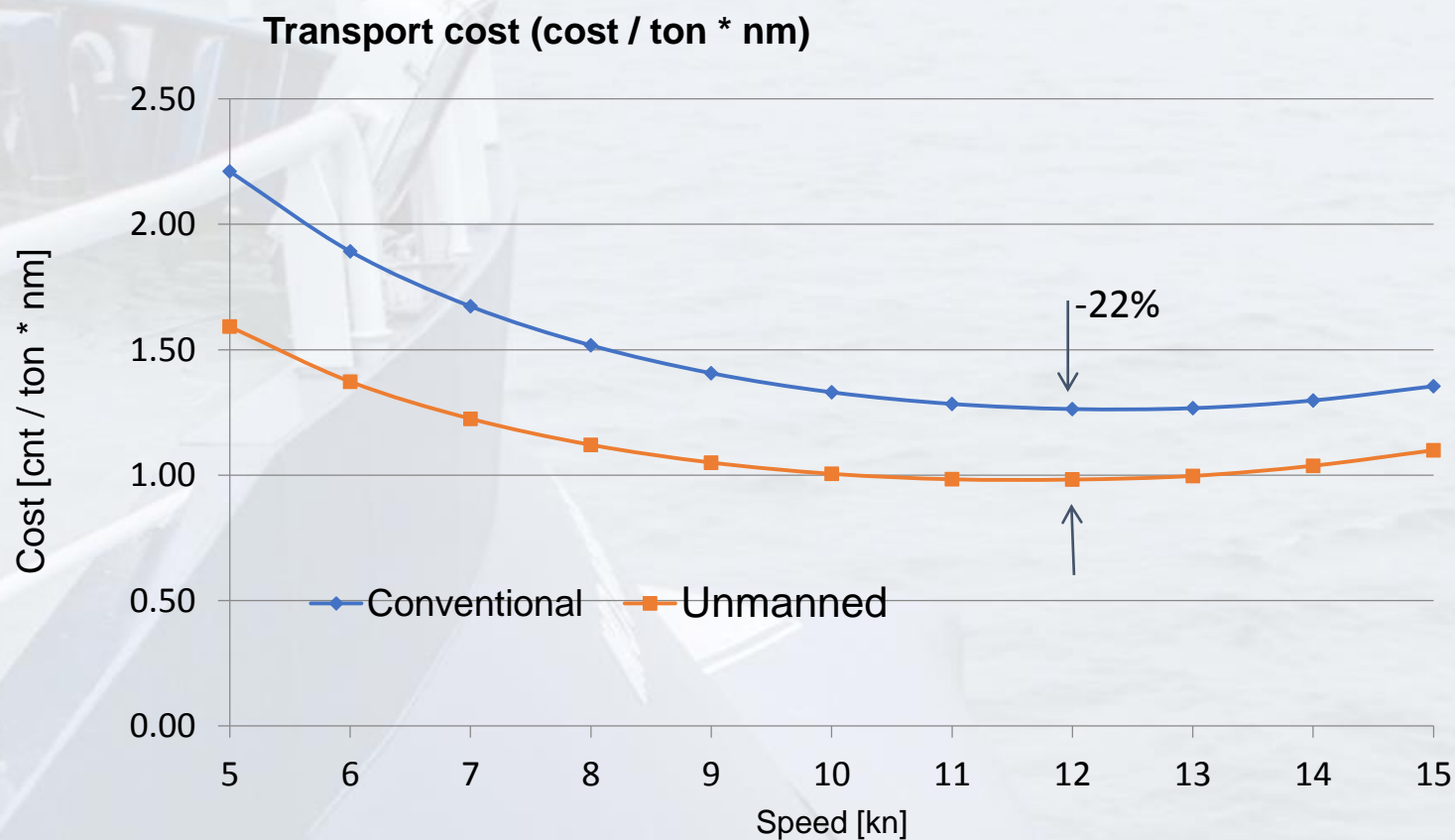
General cargo annual costs



Source: RR internal study

RR Internal Study of 20 000 dwt general cargo vessel

Why R&A Vessels – Transport Cost



RR Internal Study of 20 000 dwt general cargo vessel

Why R&A Vessels - Energy/Emissions reduction

Machine Learning

Lower weight: 700 – 1,000 tonnes

Wind resistance: ~1% saving

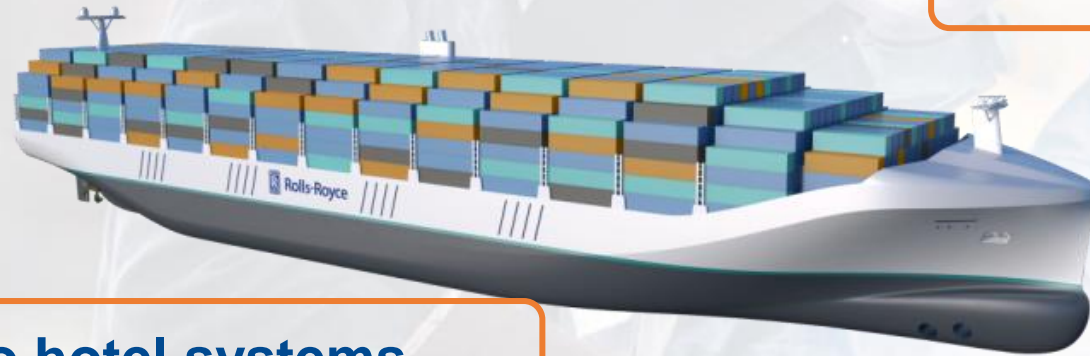


Reduced hotel load: 200 – 270 kW

10-15% fuel savings

Source: RR internal study

Remote and Autonomous ships - features



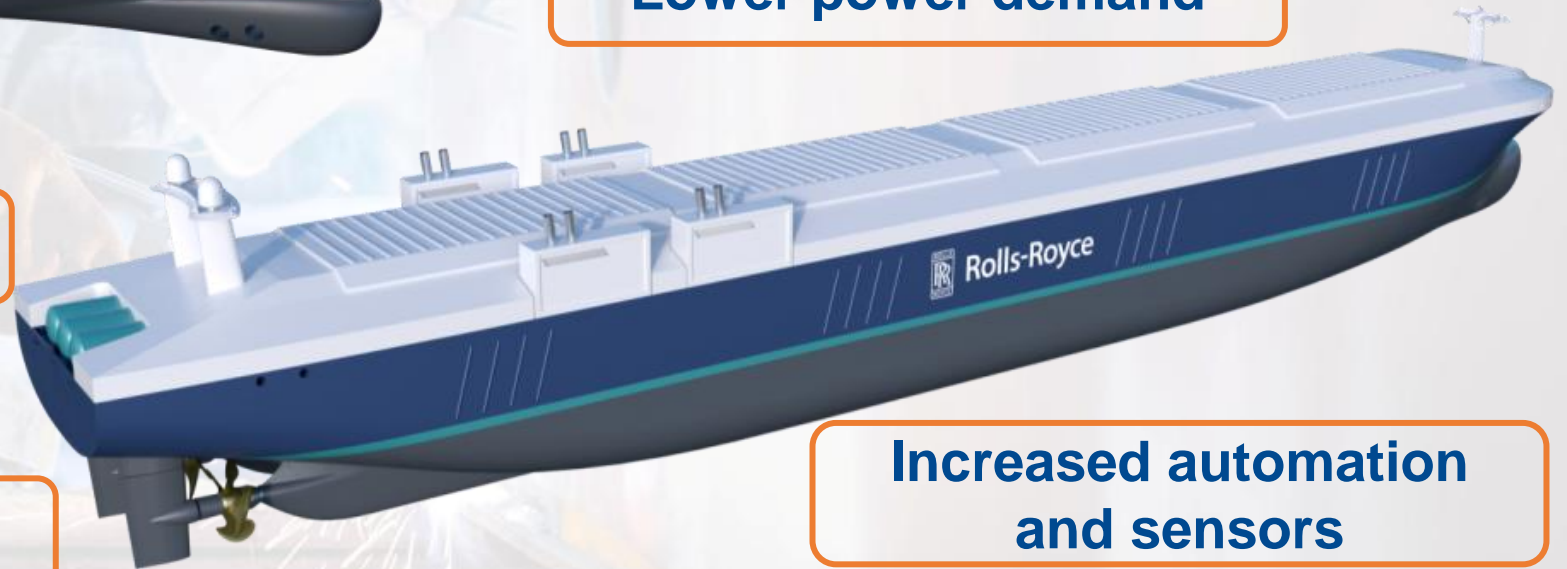
More cargo

No hotel systems

Lower power demand

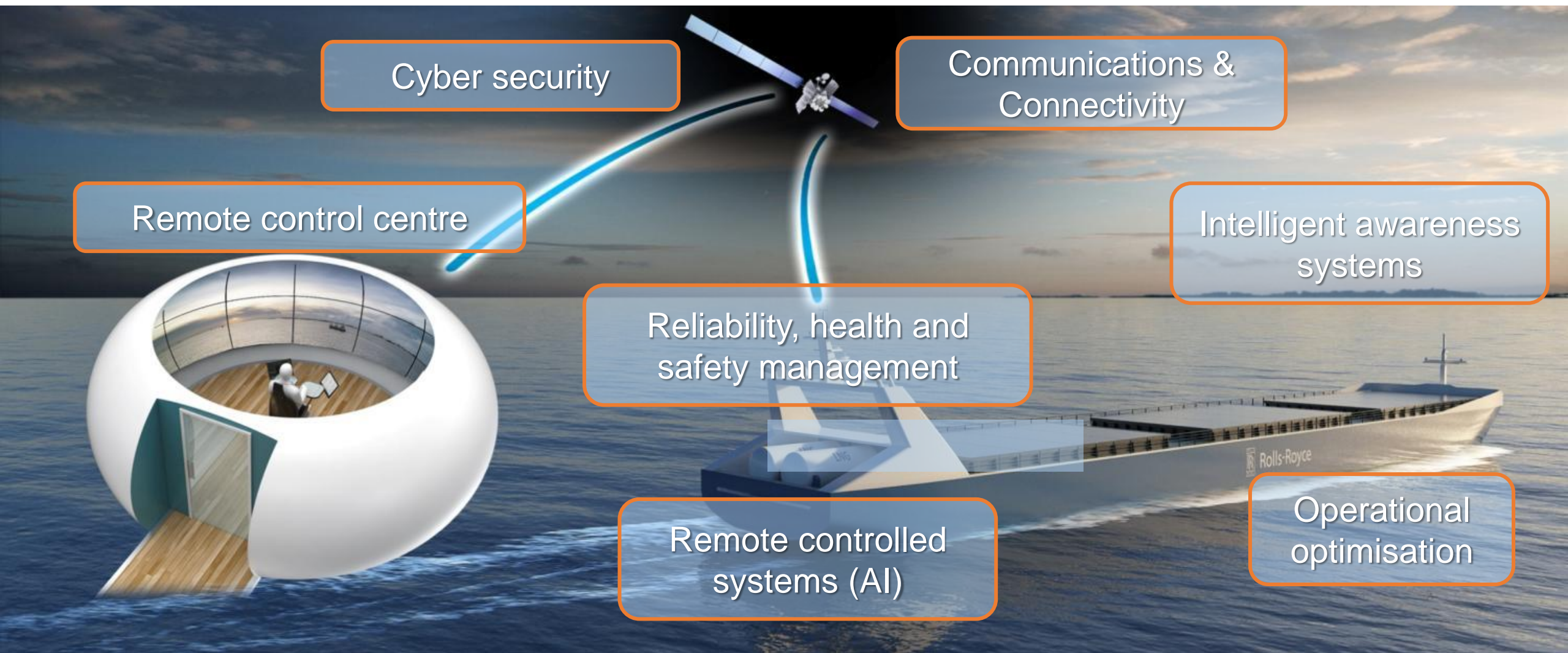
No deck house

Redundant machinery



**Increased automation
and sensors**

Technology Development Areas



Standardized systems

Validation

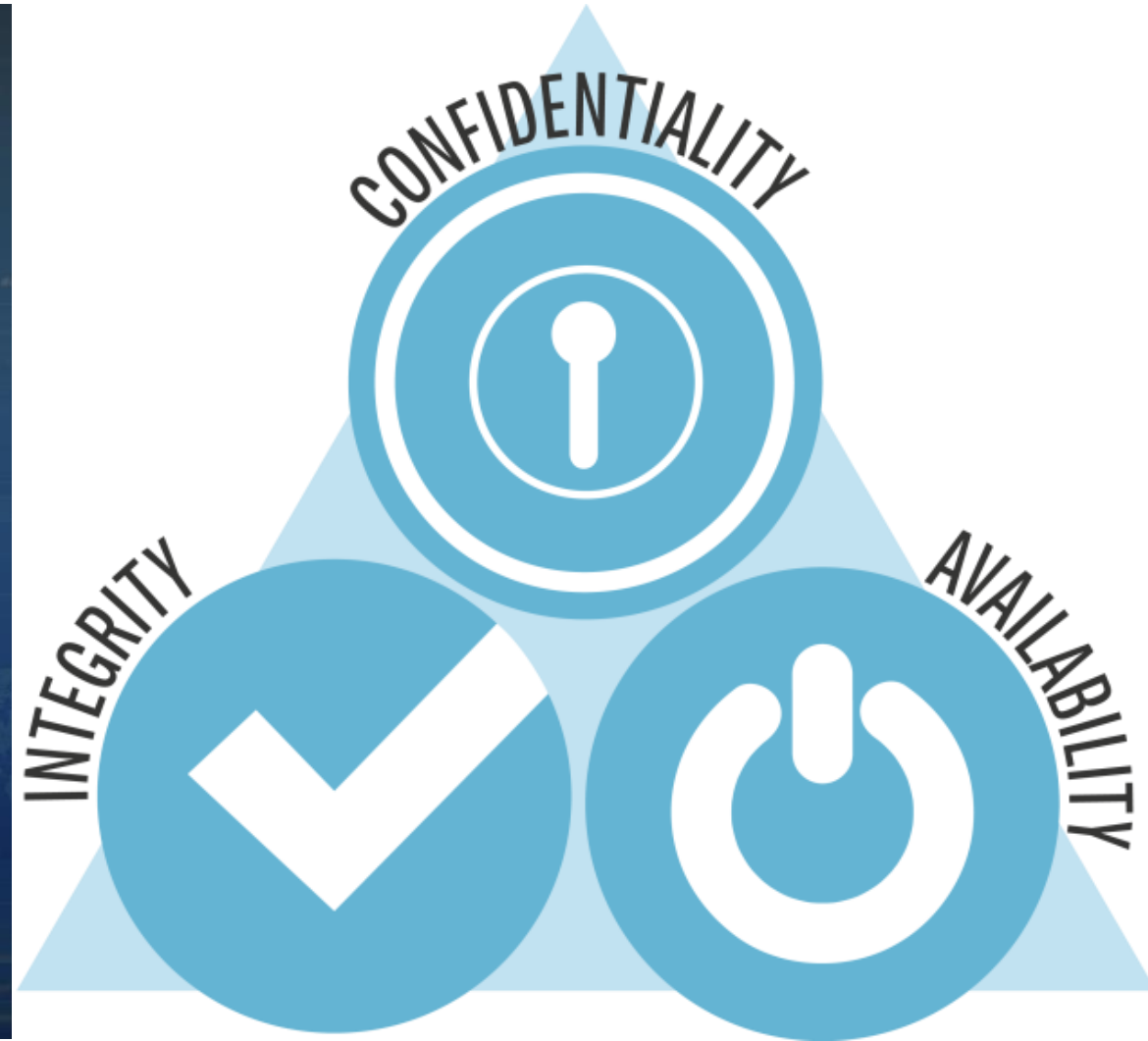
Digital twin

Sensors & trending

Health management



Cyber security

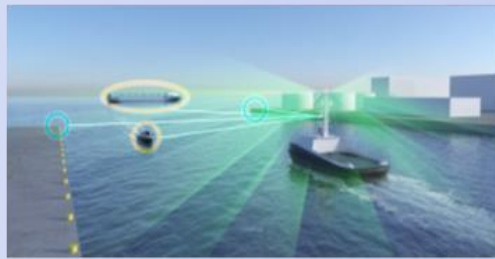


Safety

A fundamental question for us: 'can it be trusted?'

A phased
market
adoption
plan

ADVISORY



CONTROL



AUTONOMOUS



'ALARP' - As Low As Is Reasonably Practicable
safety philosophy

Fundamental Principles for Safety

Fundamental Principles		
FP1	Responsibility for Safety	The prime responsibility for safety must rest with the person or organisation responsible for the activities that give rise to the risk.
FP2	Leadership and Management for Safety	Effective leadership and management for safety must be established and sustained throughout the systems life cycle
FP3	Safety Assessment	The 'dutyholder' must demonstrate effective understanding of the potential hazards and their control for the autonomous infrastructure through a comprehensive and systematic process of safety assurance
FP4	Prevention of Accidents	All reasonable practicable steps must be taken to prevent and mitigate accidents.
FP5	Emergency Preparedness and Response	Arrangements must be made for emergency preparedness and response in the event of a total failure of the ships or its infrastructure.

Assuring Safety – ‘Defence in Depth’ for Marine Autonomous Infrastructures.

The concept of defence in depth should be applied so that:

- a) deviations from normal operation and failures of the ship, systems and autonomous infrastructure are prevented;
- b) any deviations from normal operation are allowed for by design that enable timely detection and action that prevents escalation;
- c) inherent safety features, fail safe design and safety measures are provided to protect against fault conditions progressing into accidents; and
- d) additional measures are provided to mitigate the consequences of accidents, especially severe accidents.

Objective of each level of protection;

- **Objective** Level 5 Mitigation of accident consequences through emergency responses.
 - **Defence/Barrier** Emergency control and on- and off-site emergency response (e.g. Salvage, fire-fighting tugs, transfer of control from the ROC, Security procedures in place, etc).
 - Examples: Vessel out of operation (not under command) and drifting towards a main shipping lane. Terrorist attack, earthquake, flooding event

Additional Requirements (Constrains & Opportunities)



Technology



Legal



Regulations



Insurance



Liability



When?



Jobs



Qualifications

Systems Engineering principles for Autonomous Infrastructure

- Based on Principles derived from the Royal Academy of Engineering:-
 - Principle 1: Debate, define, revise and pursue the purpose
 - Principle 2: Think holistically
 - Principle 3: Follow a systematic procedure
 - Principle 4: Be creative
 - Principle 5: Take account of the people
 - Principle 6: Manage the project and the relationships

System Thinking

Holistic Thinking

- I have to look at the whole situation – the system and its environment
- I have to understand the purpose and the context of the situation

Behavioural Thinking

- I have to understand the behaviour of the system before I start the structural thinking (form follows functions)
- I have to consider the feedback and the “delay” structure between the elements

Structural Thinking

- I have to look for structure, and the “connections” and the “dependencies” between the element.

Perception Thinking

- I have to look at the situation from different viewpoints

Abstract Thinking

- I have to manage complexity by prioritising details (separation of concerns)

Principle 5: take account of the people

- People are part of a system and not an external constraint.
- Challenge for the marine autonomous sector as the 'end user' can and probably will change.
- Competence and SQEP of the staff will be considerably different. Who will define the levels required?



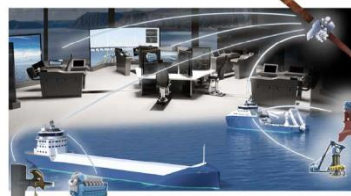
Challenge 1 - Understanding the “product”

- The “product” is the system of interest.
- ISO 15288 Section 6.4.2.1 Stakeholders needs and requirements definition process – the stakeholders requirements are defined considering the context of the system of interest with the interoperating system and enabling system.
- **System Engineering** is about agreeing the scope and context of the “product” from the outset and applying effective **system thinking** to understand the problems, managing stakeholders communication & collaboration to enable the correct decision making to derive successful systems.
- Effective system engineering framework, processes, techniques & tools can enhance the efficiency of the system engineering process.
- As the complexity of the system increases, the flexibility and the effectiveness of fit-for-purpose system engineering framework, processes, techniques & tools that will enable complexity management & the creation of multiple viewpoints will become increasingly important.

Challenge 2 – Define Future Products (Autonomy)

- System of Interest that define future products have extended beyond the vessel.
- Vessel becomes the sub-system of the “system of interest”.
- The goal of future products is to transition functionality to higher level of autonomy but extended beyond existing onboard operation & ship functions, especially decision support & decision making functionality whether onboard or offboard.
- The majority of classes of functionality of future products will be assigned to cyber-physical systems and physical systems where the **Solutions** will be targeted at autonomy Level 3-4 for a broad range of **Applications** ranging from autonomy Level 1(advisory) to Level 4 (fully autonomous) where human will focus on the sub-tasks level with system taking over the overall responsibility of the main tasks and failsafe tasks.
- **System Engineering** is required to decompose these highly complex systems (infrastructure level), derive and deliver future products, identify & manage risks, facilitate collaboration & complex system integration and address the life cycle needs of the products as the scope of the “system of interest” has changed from our current offerings.

Remote/Autonomous Infrastructure goals



System of Interests

**Operational
Modes**

Op
Mode 1

Op
Mode 2

Op
Mode 3

Op
Mode 4

Op
Mode 5

Op
Mode 6

**(Operational
Objectives)**

Operational Task / Infrastructure Functions

Sub-Systems

Vessels

ROC

Connectivity

Data Platform

Port

Others

Classification of Functions	No Autonomy (L0)	Partial Autonomy (L1)	Conditional Autonomy (L2)	High Autonomy (L3)	Full Autonomy (L4)
Monitoring			<ul style="list-style-type: none"> ➤ Functions ❖ Functions 	<ul style="list-style-type: none"> ➤ Functions ❖ Functions 	<ul style="list-style-type: none"> ➤ Functions ❖ Functions
Reporting			<ul style="list-style-type: none"> ➤ Functions ❖ Functions 	<ul style="list-style-type: none"> ➤ Functions ❖ Functions 	<ul style="list-style-type: none"> ➤ Functions ❖ Functions
Decision Support			<ul style="list-style-type: none"> ➤ Functions ➤ Functions 	<ul style="list-style-type: none"> ➤ Functions ➤ Functions 	<ul style="list-style-type: none"> ➤ Functions ➤ Functions
Decision Making	Transition functionality to higher level of autonomy including but beyond existing operation & vessel functions		<ul style="list-style-type: none"> ➤ Functions ➤ Functions 	<ul style="list-style-type: none"> ➤ Functions ➤ Functions 	<ul style="list-style-type: none"> ➤ Functions ➤ Functions
Decision Execution			<ul style="list-style-type: none"> ➤ Functions ➤ Functions 	<ul style="list-style-type: none"> ➤ Functions ➤ Functions 	<ul style="list-style-type: none"> ➤ Functions ➤ Functions

❖ **Cyber-Physical Systems (any location)**

❖ **Physical Systems (any location)**

❖ **Human (any location)**

How Autonomous is the System?

- Broad product range with a mixture of manual, automated, remote control, semi-autonomous and, autonomous features.
- “How autonomous is the system?”
- This question can be answered with an **assessment of how independent the system is in accomplishing its tasks without human interaction and human intervention.**
- It is not possible to assess how autonomous the system is without the understanding of automation.
- The key questions to be addressed include:
 - “What tasks (types) do we want to automate?”
 - “What are the level of automation intended for the targeted tasks?”
 - “What is the role of the human in the loop?”
 - “Who/what is in control for the sustained operational tasks?”
 - “Who/what takes over control in fail safe situation?”
 - “What is the autonomous capabilities of the platform?”

Lesson Learned from other Sectors

EXISTENT WORK "Sheridan" Model	
1) Computer offers no assistance, human must do it all.	
2) Computer offers a complete set of action alternatives, and	
3) narrows the selection down to a few, or	
4) suggests one, and	
5) executes that suggestion if the human approves, or	
6) allows the human a restricted time to veto before automatic execution, or	
7) executes automatically, then necessarily informs the human, or	
8) informs him after execution only if he asks, or	
9) informs him after execution if it, the computer, decides to.	
10) Computer decides everything and acts autonomously, ignoring the human.	

8	The computer performs ranking tasks. The computer performs final ranking, but does not display results to the human.	4	Both human and computer perform ranking tasks, the results from the computer are considered prime.
7	The computer performs ranking tasks. The computer performs final ranking and displays a reduced set of ranked options without displaying "why" decisions were made to the human.	3	Both human and computer perform ranking tasks, the results from the human are considered prime.
6	The computer performs ranking tasks and displays a reduced set of ranked options while displaying "why" decisions were made to the human.	2	The human performs all ranking tasks, but the computer can be used as a tool for assistance.
5	The computer performs ranking tasks. All results, including "why" decisions were made, are displayed to the human.	1	The computer does not assist in or perform ranking tasks. Human must do it all.

AUTONOMY FROM START TO FINISH			
LEVEL	CONCEPT	DEFINITION	WHO'S IN CONTROL
0	Human Operation	The operator controls the machine at all times.	
1	Automation (Function-specific)	The operator has overall control of the machine and is responsible for its safe operation, but can transfer limited control over a specific function, such as a bucket or blade, to the machine.	
2	Semi-autonomous	The machine accomplishes all its defined tasks without operator interaction and is responsible for all safety-critical error-handling functions.	
3	Autonomous	The machine accomplishes all its defined tasks without operator interaction and is responsible for all safety-critical error-handling functions.	

EXISTENT WORK Army Science Board Study	
0. Manual remote control, like a remote controlled toy	
1. Simple automation	
2. Automated tasks and functions, like a Hunter	
3. Scripted mission, like an Shadow or Predator UAV	
4. Semi-automated missions with simple decision making, like an Cruise Missile	
5. Complex missions-specific reasoning	
6. Dynamically mission adaptable	
7. Synergistic multi-mission reasoning	
8. Human-like autonomy in a mixed team	
9. Autonomous teams with unmanned leader or mission manager	
10. Autonomous conglomerate	

- What tasks (types) do we want to automate?
- What are the level of automation intended for the targeted tasks?
- What is the role of the human in the loop?
- Who/what is in control for the sustained operational tasks?
- Who/what takes over control in fail safe situation?
- What is the autonomous capabilities of the platform?











SAE Level	Name	Narrative Definition	Execution of Steering and Acceleration/Deceleration	Monitoring of Driving Environment	Failback Performance of Dynamic Driving Task	System Capability (Driving Modes)
0	Human driver monitors the driving environment	The full-time performance by the human driver of all aspects of the dynamic driving task, even when enhanced by warning or intervention systems.	Human driver	Human driver	Human driver	n/a
1	Driver Assistance	The driving mode-specific execution by a driver assistance system of all aspects of the dynamic driving task with the expectation that the human driver performs all driving aspects of the dynamic driving task.	Human driver and system	Human driver	Human driver	Some driving modes
2	Partial Automation	The driving mode-specific execution by a driver assistance system of all aspects of the dynamic driving task with the expectation that the human driver performs all driving aspects of the dynamic driving task.	Human driver	Human driver	Human driver	Some driving modes
3	Conditional Automation	The driving mode-specific execution by an automated driving system of all aspects of the dynamic driving task with the expectation that the human driver will respond appropriately to a request to intervene.	System	System	Human driver	Some driving modes
4	High Automation	The driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task, even if a human driver does not respond appropriately to a request to intervene.	System	System	System	Some driving modes
5	Full Automation	The full-time performance by an automated driving system of all aspects of the dynamic driving task under all roadway and environmental conditions that can be managed by a human driver.	System	System	System	All driving modes

Existent Work					
Level	Level Description	Observation Perception Situation	Decision Making	Capability	Example
1	Remote Control	Remote control signals received by operator	None	Remote operation is inherently simple, necessary automation.	Basic teleoperation
2	Remote Control vehicle from knowledge	Local posn, dist, head, and depth range display the operator	Basic health and vehicle state reporting	Remote operation is relatively simple, necessary automation.	Teleoperation with operator knowledge of presence of environment
3	Pre-planned mission or route	2D/3D map, waypoints, obstacle avoidance	2D/3D map, waypoints, obstacle avoidance	Basic path following with operator help	Pre-planned path, waypoints, or operator without obstacle avoidance
4	On-board processing of sensory inputs	Perception of simple surfaces and shapes	Segmentation of scene environment	Refined leader follower with operator help	Pre-planned path, waypoints, or operator without obstacle avoidance
5	Simple obstacle detection and avoidance	Local perception and map database	Basic perception and map database	Basic crew with simple autonomous capabilities	Crew country with simple autonomous capabilities
6	Complex obstacle detection and avoidance	Perception and world model representation of local environment	Perception and world model representation of local environment	Crew country with simple autonomous capabilities	Crew country with simple autonomous capabilities
7	Multiple object detection and tracking, assessed and adjusted autonomous driving	Local scene from within a point cloud of each object, with autonomous driving	Perception and world model representation of local environment	Crew country with simple autonomous capabilities	Crew country with simple autonomous capabilities
8	Cooperative operation, context awareness, no-collision traffic	Real-time fusion of data from all sensors, local knowledge of rules of the road	Perception and world model representation of local environment	Crew country with simple autonomous capabilities	Crew country with simple autonomous capabilities
9	Collaborative operation, traffic, signs and signals, own location levels of driving skill	Perception in bad weather and difficult environmental conditions	Perception in bad weather and difficult environmental conditions	Crew country with simple autonomous capabilities	Crew country with simple autonomous capabilities
10	Full autonomy with human levels of performance or better	Crew fusion from all participating hardware/software	Perception in bad weather and difficult environmental conditions	Crew country with simple autonomous capabilities	Crew country with simple autonomous capabilities

PACT Locus of Authority	Computer Autonomy	PACT Level	Sheridan & Verplank Levels of HMI
Computer Monitored by pilot	Full	5b	Computer does everything autonomously
Computer backed up by pilot	As needed	4b	Computer chooses action, performs it unless human disapproves
		4a	Computer chooses action & performs it if human approves

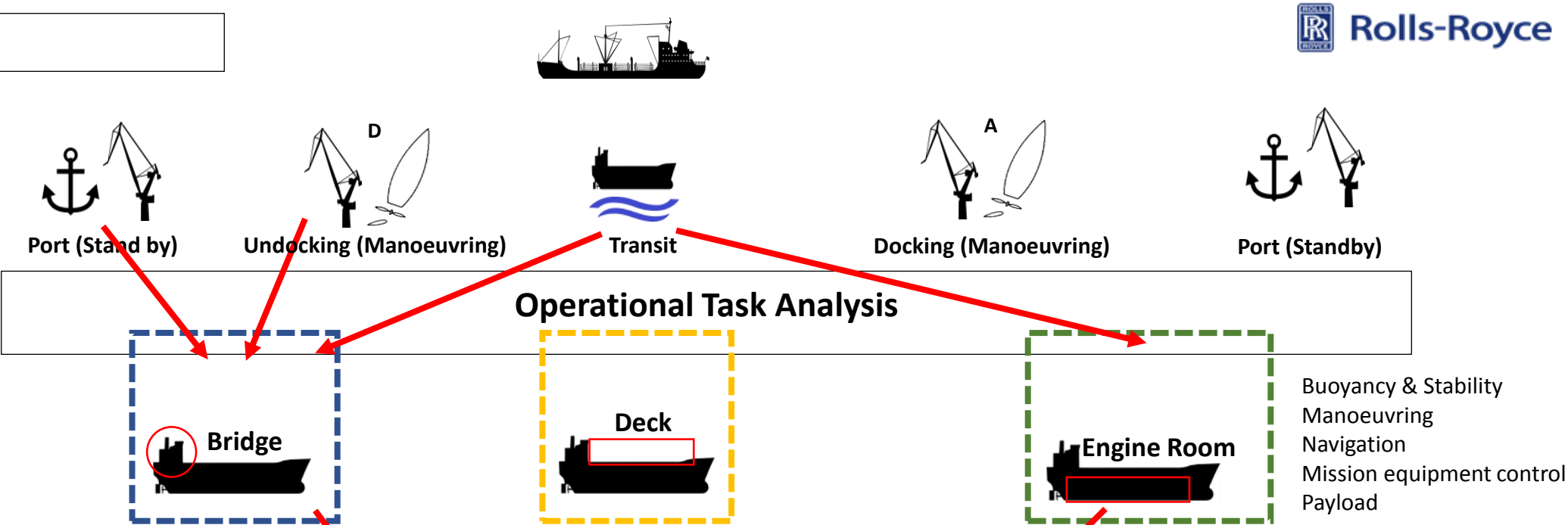
Level	HF consideration for safety	Notes
AL 0: Manual – no autonomous function.	As existing Rules Part 6 Chapter 1 Sections 1.2, 2.3 and 3 (and equivalents in other rules)	Purpose is ensuring control by competent crew
AL 1: On ship decision support	As existing Rules Part 6 Chapter 1 Sections 1.2, 2.3 and 3 (and equivalents in other rules)	Purpose is ensuring control by competent crew
AL 2: On and off ship decision support	As existing Rules Part 6 Chapter 1 Sections 1.2, 2.3 and 3 (and equivalents in other rules)	Provisions are added a) because of increasing cultural pressure from ashore for the ship to comply with direct instruction, b) when advice is provided by a computer system there is a tendency for less experienced officers to not question computer output.
AL 3: Active human in the loop	As existing Rules Part 6 Chapter 1 Sections 1.2, 2.3 and 3 (and equivalents in other rules)	If these provisions are not the case, and the exclusion is not accepted by the client, LR would need to see evidence of how the additional risks are addressed for each applicable Decision Support System.
AL 4: Fully autonomous	As existing Rules Part 6 Chapter 1 Sections 1.2, 2.3 and 3 (and equivalents in other rules)	Full implementation of existing Rule requirement should be adequate to ensure safe operation of such systems (see Ships PS C.1.5.1).

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AL 0: Manual – no autonomous function.	As existing Rules Part 6 Chapter 1 Sections 1.2, 2.3 and 3 (and equivalents in other rules)	Purpose is ensuring control by competent crew
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AL 4: Fully autonomous	As existing Rules Part 6 Chapter 1 Sections 1.2, 2.3 and 3 (and equivalents in other rules)	Full implementation of existing Rule requirement should be adequate to ensure safe operation of such systems (see Ships PS C.1.5.1).

Level	Name	Definition (Proposed Maritime Autonomy Framework)	Who is in Control? Sustained operational task	Who takes over control? Fail Safe Operational Task	System Capability
0	No Autonomy	All aspects of operational tasks perform by human operator even when enhanced with warning or intervention system. Human operator safely operates the system at all time. (e.g. Select pumps)	 Manual		n/a
1	Partial Autonomy	The targeted operational tasks perform by human operator but can transfer control of specific sub-tasks to the system. The human operator has overall control of the system and safely operates the system at all time. (e.g. start engine sequence)	 Automation		Some Operational Tasks
2	Conditional Autonomy	The targeted operational tasks perform by automated system without human interaction and human operator perform remaining tasks. Human operator is responsible for its safe operation.	 Semi-Autonomous		Majority of Operational Tasks
3	High Autonomy	The targeted operational tasks perform by automated system without human interaction and human operator perform remaining tasks. System is responsible for its safe operation. (e.g. PMS, DP)	 Semi-Autonomous		Majority of Operational Tasks
4	Full Autonomy	All operational tasks perform by an automated system under all defined conditions.	 Full Autonomous		All Operational Tasks

Vessel goals

Operational Modes
(Operational Objectives)



Classification of Functions	No Autonomy (L0)	Partial Autonomy (L1)	Conditional Autonomy (L2)	High Autonomy (L3)	Full Autonomy (L4)
Monitoring	❖ Functions				
Reporting			❖ Functions		
Decision Support	➤ Functions	➤ Functions	➤ Functions		
Decision Making	➤ Functions				
Decision Execution			➤ Functions		

❖ Systems In ROC

❖ Human In ROC

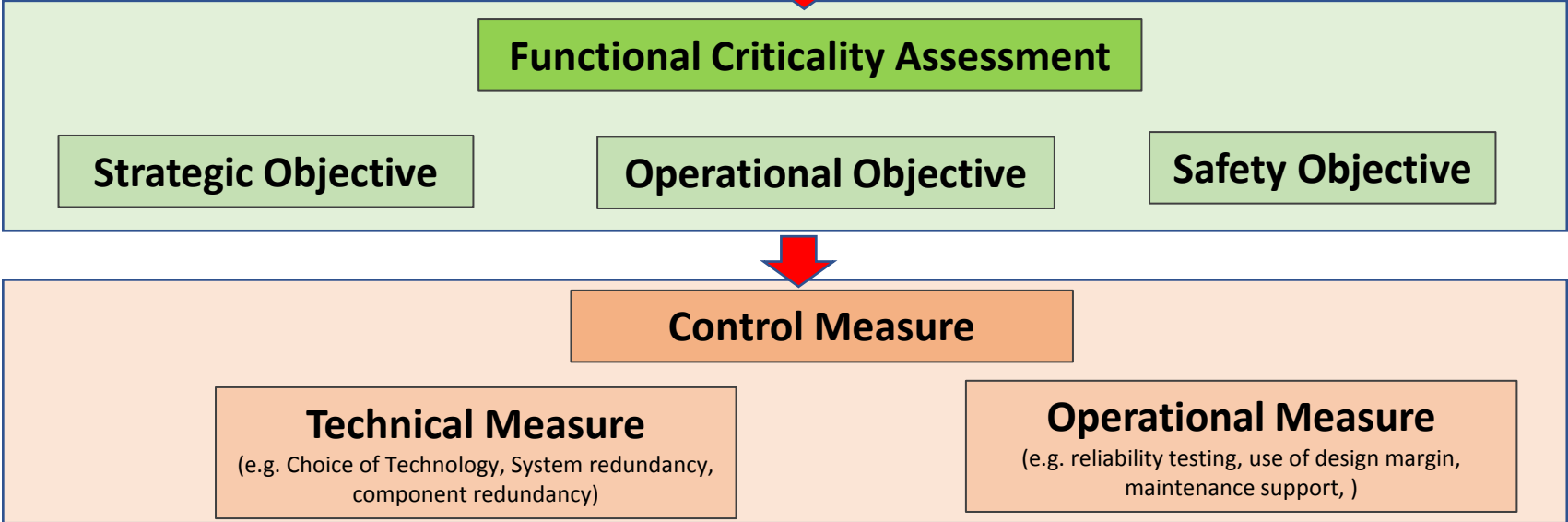


➤ Systems On Vessel

➤ Human on Vessel

Infrastructure
(Connectivity, Data)
Technology
HMD Handover
Risk

Classification	No Autonomy (L0)	Partial Autonomy (L1)	Conditional Autonomy (L2)	High Autonomy (L3)	Full Autonomy (L4)
Monitoring	<ul style="list-style-type: none"> ➤ Functions ➤ Functions ❖ Functions 	<ul style="list-style-type: none"> ➤ Functions ➤ Functions 	<ul style="list-style-type: none"> ➤ Functions ➤ Functions ➤ Functions 	<ul style="list-style-type: none"> ➤ Functions ➤ Functions ➤ Functions 	<ul style="list-style-type: none"> ➤ Functions ➤ Functions
Reporting		<ul style="list-style-type: none"> ➤ Functions ➤ Functions 	<ul style="list-style-type: none"> ➤ Functions ➤ Functions 	<ul style="list-style-type: none"> ➤ Functions ➤ Functions 	<ul style="list-style-type: none"> ➤ Functions ➤ Functions
Decision Support	<ul style="list-style-type: none"> ➤ Functions ➤ Functions ❖ Functions 	<ul style="list-style-type: none"> ➤ Functions ➤ Functions 	<ul style="list-style-type: none"> ➤ Functions ➤ Functions 	<ul style="list-style-type: none"> ➤ Functions ➤ Functions 	<ul style="list-style-type: none"> ➤ Functions ➤ Functions
Decision Making	<ul style="list-style-type: none"> ➤ Functions ➤ Functions ❖ Functions 	<ul style="list-style-type: none"> ➤ Functions ➤ Functions 	<ul style="list-style-type: none"> ➤ Functions ➤ Functions 	<ul style="list-style-type: none"> ➤ Functions ➤ Functions 	<ul style="list-style-type: none"> ➤ Functions ➤ Functions
Decision Execution		<ul style="list-style-type: none"> ➤ Functions ➤ Functions 	<ul style="list-style-type: none"> ➤ Functions ➤ Functions 	<ul style="list-style-type: none"> ➤ Functions ➤ Functions 	<ul style="list-style-type: none"> ➤ Functions ➤ Functions



Support assessment of business, operational and safety risk

Monetise risk control measure

ISO 20815:2008

Petroleum, petrochemical and natural gas industries – Production assurance and reliability management

Technical measures

- Choice of technology
- Redundancy at system level
- Redundancy at equipment or component level
- Functional dependencies
- Capacities
- Instrumentation/automation philosophy
- Reduced complexity
- Material selection
- Selection of make
- Man-machine interface
- Ergonomic design
- Protection from the environment
- Reliability testing
- Self-diagnosis

Operational measures

- Buffer and standby storage
- Bypass
- Flaring
- Utilization of design margins
- Spare parts
- Maintenance strategy
- Maintenance support

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The Interpretation of the Level of Autonomy

- A System engineering approach to use case generation for risk assessment:
 - The context include the infrastructure – vessels, ports and remote operational centres
 - Identify the vessel / fleet objectives or goals
 - Identify the vessel operational modes
 - Determine functions for all targeted vessel operational modes
 - Classify functions type
 - Assign level of autonomy to functions
 - Assign functions to be performed to actors (an actor can be human or system)
 - Determine location of the actors (location can be remote or onboard)
- There is a need to segregate the interpretation of level of autonomy according to:
 - **Specific function(s)** (e.g. different functions may have different level of autonomy, functions may change their level of autonomy over time)
 - **Specific solution(s) in question** (e.g. how functions with different level of autonomy integrated to form a solution (e.g. sub-system) with a defined level of autonomy)
 - **The specific vehicle platform in addressing its overall strategic objective(s) or goal(s)** (e.g. how different solutions with varying level of autonomy integrated to deliver the vessel autonomous capability to accomplish its overall mission).
- Having an appropriate taxonomy to define the level of autonomy for maritime operation enable safety critical function and safety critical system to be identified.

The Attributes of An Effective Maritime Autonomy Framework

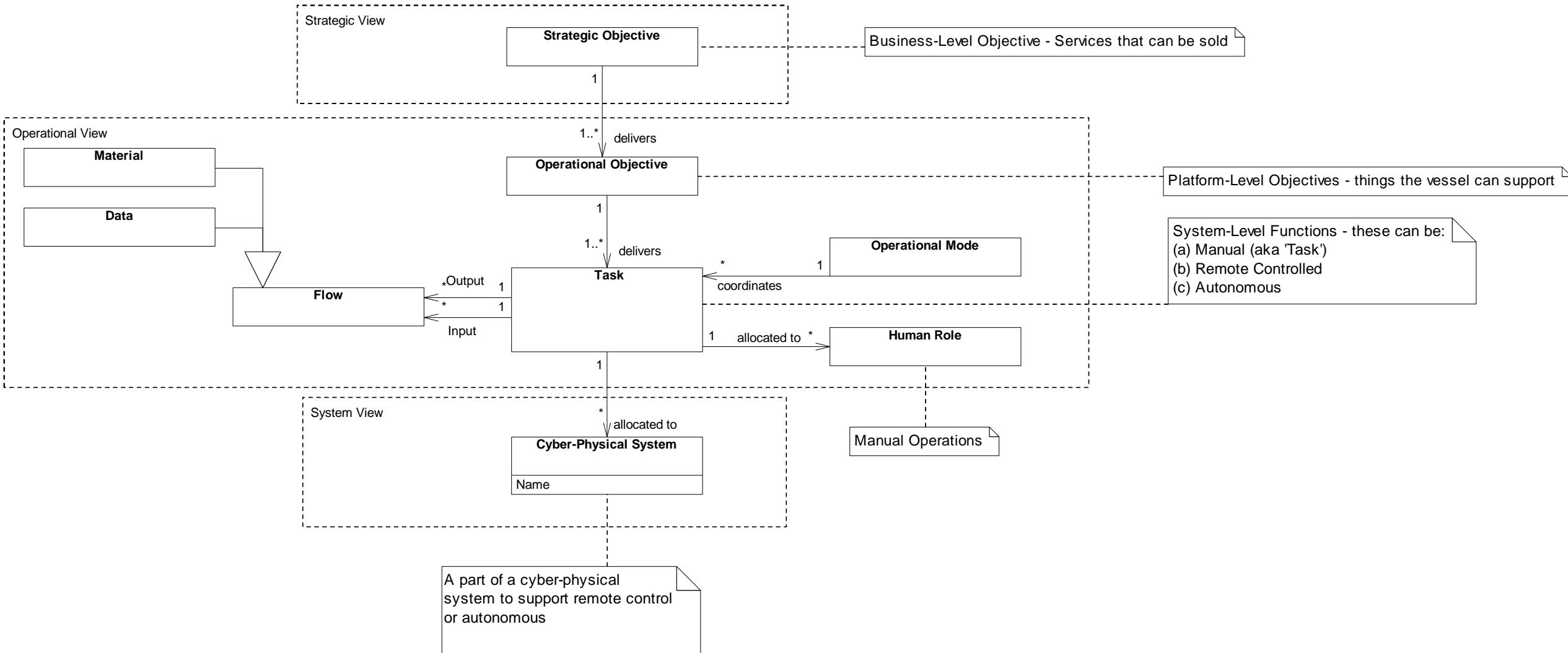
An effective MAF should be:

- **Simple** enough to be understood and remembered.
- **Practical** enough to be used in the design process & implementation.
- **Flexible** enough to cover a wide range of operational scenario and solutions at all levels (function, sub-system, system, platform level) with mixtures of autonomous features. The framework can be further extended to show technology readiness.
- **Robust** enough to provide consistency, traceability, evidence and argument to support strategic, operational, safety objectives.
- **Transparent** enough to be understood by the regulators how the safety argument has been achieved. Support customers map the value creation to the level of autonomy.

Method & Tool

- **System Engineering** defines an approach for realising successful systems.
- **Model-based System Engineering (MBSE)** provides an approach for using Models to realise the artefacts of a System based on a set of modelling Views.
- We are using MBSE to model the artefacts of the Maritime Autonomous Enterprise System (infrastructure) where the **Enterprise Architecture Framework / Maritime Autonomy Framework (MAF)** provides a standardised way of defining the Enterprise (structure & content).
- We are using **MBSE tool** to implement the Enterprise Architecture Framework / MAF for the Maritime Autonomous Enterprise System.

Domain-Neutral Terminology



Domain-Specific Terminology

Example Task: **Leaving...**

- **Berth**
- **Dock**
- **Anchor**
- **Mooring**
- Each task description is different
- Post-condition of task is similar (if not the same)

Agreement on domain-specific terminology is essential for
integration and interoperability

Key Take Away

- System Thinking – how do we nurture system thinking in our enterprise community?
- Autonomy - To help us truly understand the engineering challenges of autonomy, look beyond engineering
 - Neuroscience, psychology and computer science – combine their theories, findings, evidence to derive new insights
- Managing complexity - Einstein’s “everything should be as simple as possible, but no simpler”.
- Four stages of competence:
 - Unconscious incompetence
 - Conscious incompetence
 - Conscious competence
 - Unconscious competence
- We can’t afford to be unconscious incompetence when designing & deploying autonomy. Our starting position need to be at least Conscious Incompetence, conscious about what we don’t know and don’t know enough, understand the limitation & opportunities, know where the risks are and how to manage them to ensure safe deployment.