Outside the matrix
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Introduction
Simulation is a key enabling technology in the drive to deliver the second generation of smart maritime platforms. Developing systems to enhance training, planning, operations, procurement, and R&D activities, among many others, cannot be considered in isolation as they subsume a broad spectrum of multi-disciplinary and trans-sectorial R&D effort. In addition, maintaining a highly skilled workforce to maximize the return from what are knowledge and capital intensive technologies is critical. Existing and emerging systems have clearly benefitted to a great extent from relevant exponential engineering advancements over the past decade. By leveraging advancements in computational capacity, battery storage, sensor miniaturization, communications/networking, and software intelligence, R&D teams across the industry are steadily unlocking the potential of autonomous sensing, actuation, and control as the barriers posed by the fusion of unstructured big data sources characterizing subsea workflows are slowly eroded.

Success to date is evidenced by the increasingly automated nature of solutions assimilated into routine subsea workflow processes. Supervised bathymetry data processing algorithms, such as CUBE from the University of New Hampshire, have existed as industry standard solutions for over a decade. Such algorithms decrease manual workload and turn-around time in converting raw data into deliverable products and revolutionize surveyor work and quality control processes by making client-ready data available for assessment within the on-ship acquisition cycle. Our industry, in line with a worldwide movement towards machine learning, is focused on workflow mechanization; for example, Caris’s Onboard product line is transferring supervised PC software solutions onto autonomous platforms. This is coupled with reinvigorated moves towards integrating various combinations of autonomous aerial, surface, and underwater platforms into routine oceanographic data acquisition operations. Published sea trial results, such as a series of NOAA ship Ferdinand R. Hassler trials with the Kongsberg-Hydroid REMUS AUV, demonstrate significant improvements in efficiency and dataset quality while current efforts in running swarms of such platforms in tandem should offer even greater gains.

Finally, in an industry continually reshaping due to mergers and acquisitions, the evolving commercial landscape will undoubtedly reflect disruptive technology trends and many sonar software and instrument manufacturers are now in the same conglomerate stables as AUV manufacturers delivering integrated solutions to target markets. Example pairings include QPS / Saab, Reson / Gavia, Kongsberg / Hydroid, and Seabyte / Bluefin.

As they have matured through operational readiness and widespread industry proliferation, the impact of successive first generation systems has catalyzed R&D focus on broadening the robustness, functionality, and decision making skills of current solutions beyond the boundaries of pre-programmed, supervised, and single mode operations. Next generation systems are required to be predictive and adaptive, equipped with the capability to autonomously make accurate data-driven decisions in real-time, and are expected to be as comfortable in cluttered shallow water environments as in the clear and open deep waters. This requires advanced feature identification, tracking, classification, and intervention capabilities driven by automated sonar based machine vision.

The lack of turn-key machine vision intelligence is one of the principal factors limiting the ubiquitous emergence of these systems. Intensive R&D into sonar-driven autonomous technologies ultimately requires a cost efficient supply of diverse real-world representative data to support a financially feasible design cycle process. The only realistic way is exploiting simulation to cut design cycle costs, improve system reliability, and bring systems onto sea acceptance tests more rapidly. In addition, the smarter the
systems become so too the skill sets required by industry personnel as roles become progressively crowded out by automated processes from the low level tasks upwards.

Simulation platforms as distinct from standalone simulators are required, supporting an ecosystem of technologies and applications from an integrated systemic framework that can support all aspects of the underwater sonar workflow including R&D, training, planning, and in-the-field operations. SonarSim has conducted a number of pilot projects over the past number of years which have provided insight into the role simulation can play as a key enabling technology in the delivery of wider industry goals. The remainder of this essay will discuss these simulation projects and give a historical background to the sector from a hardware and software perspective.

**Historical Background**

Modelling and simulation are distinct research topics with unique sets of challenges and their evolution has been characterized by contributions from many different disciplines and sectors throughout the various phases of their respective histories. In general, the simulation community makes software contributions to the field of computational ocean acoustics while subsuming the mathematical equations and physics theory of the modelling literature. Simulation performance requirements need to keep pace with the state-of-the-art in survey technology in an industry traditionally characterized as a technology laggard but is now keeping pace with contemporary ICT trends.

Up to the 1960s the vast majority of technical innovation in the subsea theatre was driven by naval spending and applied to anti-submarine warfare, mine detection, etc. Modelling efforts within academia were mainly focused on understanding of the underlying physical processes and their mathematical representations. The unavailability of computational technology required most modelling tasks to be carried out by hand. However, from the 1960s onwards major industry changes were driven via new enabling technologies, beginning with the advent of digital signal processing.

The 1970s saw the explosion of commodity hardware CPU and FPGA technologies with Moore’s law [Editor’s note: the principle that
overall processing power for computers will double every two years (mooreslaw.org)] driving performance improvements. It was also the beginning of improved graphics due to the advent of GUI driven operating systems and the dawn of video gaming. In the midst of these technical leaps, analogue side scan sonars saw commercial production, with data visualization and sonar control limited to printer based paper plotting and ping triggering. However, increasing computational power coupled with software for programming unlocked tractable complex acoustic simulation for mainstream civilian applications. The mathematical formulas contained in complex models could be translated directly into source code, the output response evaluated over time, variables manipulated, and the resulting information presented onscreen.

The 1990s saw the advent of multibeam systems which exploited increasingly complex parallel FPGA architectures for data processing. Full wave field FDTD and PSTD modelling methods became active areas of research for sonar transducer directivity and acoustic propagation modelling. Offline high-frequency sonar models simulation based on acoustic ray-tracing was another new area of research. Increasingly accurate inverse models of backscatter acoustics in terms of frequency, sediment properties, and angular response opened up the area of forward seabed classification. The area of visualization was becoming increasingly important with many hydrographic software companies formed in the early 1990s and furnished with 3D data rendering.

At the beginning of the 2000s, operational simulators for training such as early ship-bridge and ROV simulators entered the marketplace. Backscatter models for object detection and seabed classification were brought from R&D into industry through products like Geocoder. Major steps in workflow processes became automated through algorithms such as CUBE. The data produced from survey systems steadily increased moving from side scan backscatter, multibeam depth, multibeam backscatter, multibeam snippets to recording full water column data. The quality of data acquisition has steadily increased along with the tightening of tolerances for successful system mobilization. The order of magnitude increase in sonar data volumes has been matched by similar explosions in 3D visualization, animation, and gaming polygon counts providing tailor made advancements in hierarchical data management, spatial segmentation, and parallelization to solve the related problems of maritime data visualization, processing, and simulation.

The past few years has seen the blurring of lines between simulation and operations. Structural analysis simulation of subsea components, previously limited to initial design development, has moved into the area of feeding real-time structural loading readings into simulation for stress and point of failure prediction. The complexity of personnel training has led to the development of training simulation for high-resolution hydrographic survey (Figure 1). The shifting value proposition of survey vessels and equipment due to pressures such as oil prices has led to the sell-off and retooling of survey companies but simulation driven analysis can ensure profitable utilization of capital and personnel resources.

Current market forces, achievements in artificial intelligence (AI) and automation, and limitations of current survey methods are bringing a major focus on autonomous survey systems, through the stepping stones of autonomous desktop data processing. Simulation is required in the development of autonomous survey platform software algorithms. Simulated datasets are required for the initial training of neural networks both through supervised and reinforcement learning. During operations a simulation framework can acquire sonar data, process it, and make real-time decisions in terms of the survey objectives; for example, track towards a feature of interest.
Current trends in other industries will have a major impact within the survey industry. The explosion in AI in the recent past with the development of self-driving cars, systems which can beat humans at the intuitive game “Go,” and adoption into data analytics has already been felt in survey with the rise of commercially feasible AUV/ASV-based survey systems. A major enabler of the AI trend is the use of heterogeneous computing where a mixture of computational cores (CPU/GPU/FPGA) enables the necessary performance. In addition, the scaling of computational platforms can go from a low-power multi-core GPU enabled smartphone to a cloud based HPC framework. A common sonar simulation framework can be targeted across a range of hardware scales to enable tasks from exhaustive survey fleet simulation to low-power simulation in the loop AUV operations. Current bottlenecks are being caused not only by computational limitations but bandwidth issues driven by the amount of data and the manner of its transfer in heterogeneous systems. Current industry investment is targeting these bottlenecks with new bus technologies for CPU/GPU (NvLink) and CPU/FPGA (Coherent Architecture Processor Interface [CAPI]).

Sonar simulation is a key enabling technology across sonar related R&D, procurement, planning, operations, and training. Rather than develop separate simulators to address each domain separately, the development of an integrated simulation framework which can target overarching problems in all domains is a suitable approach. While the underlying technologies and enabling infrastructure can be adopted from related technical domains to deliver the necessary computational resources, the development of a multipurpose platform ecosystem has requirements bespoke to the maritime sector.

**Training Personnel**

Our industry has a knowledge transfer choke point which affects new recruit induction, continuous professional development, after sales technical training, and project management. Similar to the experience of the airline pilot training industry, it is a space ripe for simulator enhancement, as evidenced by the successful entry of ship-bridge, dynamic positioning, and ROV simulators. A small subset of the routine day to day training challenges tackled by maritime enterprises big and small include training new staff recruited from different branches of general science and engineering into the distinct challenges of underwater survey while maintaining consistency of standards, knowledge, and expertise across various organizational roles; new procurements integrated into existing workflows; and disseminating expertise to clients.
SonarSim was originally established to solve the problems preventing the use of simulation for maritime training, specifically the use of sonar simulation for hydrographic training, as outlined in V6N2 of this journal in 2011. The identified issues, cost-benefit justification, and proposed design tenets to realize simulator based training remain largely unchanged. Technical challenges at the time related primarily to the computational demands of real-time survey-scale high-resolution sonar dataset generation. In the intervening period SonarSim has developed out the technology solution over successive INFOMAR, Science Foundation Ireland, and European Commission FP7 and H2020 funded R&D projects. The company subsequently productized the platform into a hydrography training platform which is targeted at and has sold into the International Hydrographic Organization accredited training academy sector. Having successfully solved the
computational issues, SonarSim turned its attention to harnessing this scientific computational capability into a personnel training platform, necessitating the creation of a completely new approach to training program design. Existing training programs do not readily lend themselves to the integration of simulator generated exercises and content into their existing instructor and student material without a significant overhaul and restructuring of how individual topics are delivered. To maximize the benefits of simulation, shrink-wrapped learning content must be formulated and generated from scratch which can leverage survey simulation, learning management system infrastructure, and OEM acquisition and processing software, to best meet hydrography training program learning objectives (Figure 2).

Simulator-based operational case studies unlock novel training techniques, tools, and strategies, which can be applied in designing structured learning experiences, as well as used as a measurement tool linked to targeted competencies and learning objectives. From a content perspective, real-world exemplar hydrographic data covering a wide scope of payload instrumentation configurations, system settings, and operational scenarios is excessively expensive to collect in the field and learning is constrained by only showing an extremely small subset of potential example scenarios with a limited amount of student system interaction. In simulation, practical scenarios can be created, demonstrated, and analyzed; e.g., survey system calibration, line selection, and performance check.

SonarSim has focused heavily on integrating the training datasets with industry standard acquisition and processing software from MB-System, QPS, Caris, Hypack, Kongsberg, and EIVA. The platform also required a custom suite of sonar data visualization and analysis tools as simulation can produce datasets not typically generated in the field and consequently the visualization and analysis tool have certain key features which are unique for training (Figure 3). The use of simulation as a personnel training tool is standard in many industries as is the use of simulation in new technology development. Two SonarSim R&D case study examples are outlined in the following sections.

The Evolution of Platforms
A case study of recent SonarSim R&D activities in extending its existing survey simulation framework from the training domain into a new technology testbed for multibeam sonar acquisition automation illustrates the multiplier achievable from cross-pollination of virtual and real-world functionality. The objective of the endeavour was to prototype a simulator based framework which could, through exhaustive what-if simulator scenario analysis, determine the most cost effective combination of survey vessel, payload instrumentation, and runline regime to achieve prescribed survey specifications and then re-purpose this search and analytics functionality into a smart onboard control architecture to actually deliver these performance metrics in the field. The project was part funded by INFOMAR and subsequently the European Commission, with ship trials conducted by the Geological Survey of Ireland’s RV Keary. The output has been commercialized under SonarSim’s Multibeam AutoPilot (MAP) product line; Figure 4.

One of the key market drivers common to all maritime survey sectors is the desire to increase operational efficiency and vessel utilization when mapping the seabed. This is particularly acute in shallow water sites as the complex topography and resulting swath width variations impose tight positioning tolerances to ensure gaps in coverage are prevented. The continuous on-the-fly recalculation of runlines and deviations from pre-planned vessel waypoints required to maintain desired coverage overlap between successive runlines can quickly fatigue the onboard hydrographer and helmsman with knock-on safety, productivity, and data quality implications. As a repeated problem, the impact on survey
efficiency is predictable but remains difficult to control by current methods. Analysis of archive datasets indicates 10-15% of survey time is lost through a combination of infill line elimination of holidays and coverage redundancy in areas of overly tight runline spacing.

SonarSim committed to solving this problem by developing a dedicated onboard runline planner which processes the bathymetry data collected during a runline, calculates the optimized multi-segment vessel route to achieve the next runline sounding density desired by the hydrographer, and communicates these vessel waypoints to the onboard autopilot. The primary objectives are to relieve the hydrographer of the low level task of manual runline calculation and the helmsman of manual steerage. The software is more effective at these formulaic tasks while the hydrographer is better suited to supervisory tasks related to quality control and the helmsman to maintaining safety and watch for hazards. The sought after 10-15% efficiency saving can be mined by the computational capacity of the software which can automate this stage of the planning and acquisition workflow, and significantly improve system precision by establishing a novel high performance computing feedback path between the multibeam and the vessel navigation system.

The use of simulation is central to the ongoing R&D effort. Much of the initial test stages could be conducted on a line-by-line basis using archive raw bathymetry files to verify the datagram parsing, terrain geo-referencing, surface reconstruction, and outlier filtering modules required to process the recorded beam data into a seabed representation. However, while the performance metrics of a previous survey can be accurately benchmarked from recorded data, it is not possible to verify the performance of the adaptive runline planning modules without the ability to control the navigation of the survey vessel over successive runlines. This portion of the verification and validation testing requires sea trials, which are currently underway.

Access to vessels and equipment for sea trials during the roll out phase of R&D is a
precious resource and for a majority of small organizations requires support from a larger partner institution; in SonarSim’s case, the INFOMAR program. Dedicated test vessels are the luxury of very few organizations and time spent mobilizing, integrating, and resolving technical issues at sea typically incurs the opportunity cost of relinquished survey time and can rapidly curtail a planned testing schedule. It is thus crucial that test systems arrive on ship operation ready, which can only be assured through the use of exhaustive simulator testing prior to release. While simulator testing should never displace real-world sea trials, it is an essential component in a hybrid test framework.

SonarSim’s long term objective for MAP is to progress the system to ASV and ultimately AUV applications. In tandem, the simulator testbed quality assurance criteria reflect the step change in risk budgets moving from in-situ supervised, to remotely supervised, and on to unsupervised modes of autonomous operation. Simulation as a major driver in AUV/ASV development is outlined in the next section.

Adding Intelligence to Simulations
Simulation can uniquely fulfil R&D test requirements for AUV navigation control, survey runline, target detection and tracking systems which require a plethora of training datasets to achieve supervised and reinforced learning. In 2013 SonarSim was invited to join a Framework Programme 7 European project, “SEcurity UPdate for PORTs” (SUPPORT); see Figure 5. The project scope included developing two AUV systems to detect and track moving object threats in ports via sonar image recognition. The choice of sonar was driven by a low cost bill of materials which could still achieve the necessary fidelity to detect threats in the acoustically noisy cluttered environment of a busy port. The costs and time required to undertake harbour trials made simulation an attractive candidate solution due to the number of training datasets needed in successfully training sonar-based threat detection artificial intelligence.

SonarSim delivered a machine vision support framework to accelerate the design cycle, reduce costs, and offer a level of flexibility
and control not available via field trials. The project required the development of novel simulation components for modelling the acoustic signature of schooling fish shoals, mammals, diver gas discharge, diver swim locomotion, moored and passing vessels, port walls, shallow water sea surface reverberation, and seabed backscattering.

Project partner, BMT, identified a number of sonars which fell within initial technical and budget reviews but final decision required an exhaustive what-if simulator scenario analysis of forward looking and mechanically scanning sonar systems. Through an accurate replication of the physical reality, the generated sensor data is driven by a high fidelity physics model, and signal interfaces are characteristic of onboard sensor interconnects, the transition between simulator testing and actual trials was seamless. Accurate simulation of each instrument’s operational control and logging in their native formats offered full understanding of system engineering trade-offs for each candidate sonar in terms of data density, number of beams, sampling rate, sonar control flexibility, scanning speed and coherency. Although able to carry out some simple field trials with each sonar, the exhaustive nature of simulation offered a much greater confidence level in final sonar choice. While relevant AI techniques could be identified as the final structure of data acquired, platform motion disturbance, etc. were brought to the fore by initial simulation testing.

Exhaustive simulator runs allowed thousands of execution runs to be completed and used in AI training datasets. Through following simulation driven development, two autonomous underwater vehicles were successfully demonstrated to key stakeholders at the Port of Lisbon on May 22, 2014.

Conclusions
The driver of sonar technology until the 1970s was military investment. From the 1970s on the commoditization of hardware allowed the commercial exploitation of technology which to this point was commercial infeasible. In addition, the 1970s was a time when much of the military research of previous decades was released to the public domain. The separate hardware innovations of digital signal processing, advent of Moore’s law, graphics cards, multi-core, and mixed core computational led to specific innovations in marine survey. These technical leaps allowed simulation to move through a number of phases from pure research and development, offline analysis, training of personnel and software algorithms, simulation driven decision making to finally simulation being the driver of fully automated acquisition and processing workflows.

It is possible to utilize simulation across applications, as a platform technology, with the marginal investment in training, support tools, and testbeds diminishing as the technology is introduced into successively new applications. Complementing the enhancements bestowed by simulation in smart pedagogical delivery, simulation can uniquely fulfil R&D test requirements for verifying and validating new technologies designed to improve the smart capabilities of in-the-field operational support tools. As in the context of the personnel training paradigm, once the simulator virtual environment is an accurate replication of the physical reality, the generated sensor data is driven by a high fidelity physics model, and signal interfaces are characteristic of onboard sensor interconnects, the transition between simulator testing and real-world ship trials is seamless.

The capabilities inherent at this stage of simulation technology readiness presents an opportunity for derivative and integrated technologies to emerge which can fulfil a plethora of multipurpose supporting roles such as smart resource planning, scheduling, equipment selection, and performance prediction, thereby maximizing the value added technology output and commercial impact achievable from a common underlying platform; e.g., the simulator allows one to investigate, discover, and demonstrate
optimal survey methodology solutions to advanced operational scenarios.

The disruptive move to commercial AUV/ASV systems has increased the importance of simulation in terms of both the training of AI algorithms and increasing system capabilities with simulation as a feedback and feed forward decision-making mechanism during operations. Current AUV/ASV operations are limited by the need to remove systems from the water for task reprogramming and downloading of acquired data. Increasingly complex simulation leads to greater system autonomy through automated data processing, analysis, and decision tree heuristics lessening the need for costly reprogramming; e.g., incorrect manual input of runlines, data gaps, and faults identified only after expensive off-line data processing is complete.

Although the technical challenges to increasingly automated systems are decreasing, a number of other barriers need to be overcome for broad market adoption. Important regulatory and legal responsibility questions need to be considered when humans are taken out of the loop and transition into supervisory and quality control roles. Technology can go through periods of false dawns such as artificial intelligence in the 1990s. While maritime operations are a complex and error prone process, simulation has gone through decades of use across a number of operating domains which gives the technology a strong level of maturity and integrity. The potential move towards self-driving cars and the massive impact it could have on automobile insurance and regulatory requirements, the current explosion in drones and current regulatory flux, and the general global trend to automation all have interesting parallels with the maritime sector. Simulation-driven automation allowing operational tasks to be defined in terms of what needs to be done rather than how to do it will be both a technical and regulatory challenge.

The case studies outlined along with industry trends display how simulation has gone through a number of development phases and by focusing on simulation as a platform feeding into different domains rather than as an add on to each, simulation has moved from limited R&D projects to being the major driver in improving both human and machine capabilities.

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James Riordan, B.Eng., PhD, is a Director and co-founder of SonarSim. He holds a PhD in Computation Ocean Acoustics with a background in Electronic and Computer Engineering and has been engaged in subsea technology R&D since 2002. Prior to SonarSim, Dr. Riordan was a Research Principal Investigator at the Marine Robotics Research Centre at the University of Limerick.