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Adaptive Multisensor Biomimetics Unsupervised Submarine Hunt (AMBUSH)—TIF Final Report

A summary of results, impacts, and future challenges

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Abstract

Underwater surveillance is inherently difficult because data transmission is limited and unpredictable when targets and sensors move around in the communication-opaque undersea environment. This report summarizes a three-year research project finding inspiration in Nature's collaborative tasks, such as wolves hunting in packs, to advance undersea-surveillance. The research proposes an unsupervised surveillance concept aimed at maximizing target localization and sensor covertness. This research project leverages recent technological advances to address two unique undersea challenges: intermittent communications and dynamic environmental changes. This document first reviews the scientific objectives and engineering challenges pertaining to these research activities before discussing impacts, results, and future challenges.

Significance for defence and security

Military undersea-surveillance systems usually are wired, deployed overtly in friendly waters, and requiring a significant operator/analyst overhead. As a coalition member, the Royal Canadian Navy (RCN) is often tasked to patrol or secure strategic choke points with a small number of warships and away from friendly waters. These situations keep Navy personnel and assets within the reach of an opposing force, thus requiring a high-level of readiness over long periods of time.

Today's Navy sensors enable the collection of a massive amount of data, often analyzed offline. The Navy of tomorrow will dominate by making sense of that data closer to real-time.

To increase the Navy standoff distance, the proposed undersea-surveillance network could be deployed and operated in a covert manner. Such networks will operate with minimal operator intervention while exploiting the changing undersea environment to its advantage. Other direct benefits of this research project are the reduction of submarine threat exposure, an increase in sensors' coverage, an acceleration of the first two stages of the observe-orient-decide-act (OODA) loop, and the enabling of surveillance for choke points, confined areas and ice-covered areas.

Résumé

La surveillance sous-marine est intrinsèquement complexe dû au fait que la communication et la transmission de données sont restreintes et imprévisibles en présence de capteurs et de cibles faisant preuve de mobilité. Ce document présente un sommaire d'un projet de recherche d'une durée de trois ans et s'inspirant de diverses tâches de collaboration communes dans la nature, telle la chasse collective d'une meute de loups, afin d'avancer l'état de l'art en surveillance sous-marine. Ces efforts de recherche exploitent de récentes avancées technologiques tout en visant à compenser deux caractéristiques propres à l'environnement sous-marin, soit la présence de communications intermittentes et des changements environnementaux fréquents. Cette documentation rapporte également les objectifs scientifiques ainsi que les défis technologiques associés à ce projet de recherche avant de discuster les résultats, les divers impacts, et les défis futurs.

Importance pour la défense et la sécurité

Les systèmes militaires de surveillance sous-marine sont souvent câblés, installés à découvert en eaux territoriales, et requérant la participation intensive d'un opérateur et/ou d'un analyste. En tant que membre d'une coalition, la Marine canadienne royale (MRC) est usuellement mandatée pour patrouiller or pour sécuriser des points stratégiques avec un nombre limité de vaisseaux militaires en eau non territoriale. Ces situations maintiennent la Marine et son personnel à la portée d'une force de frappe ennemie, nécessitant ainsi un niveau d'alerte élevé sur des périodes de temps prolongées.

Les capteurs actuels de la Marine permettent l'acquisition massive de données habituellement analysées a posteriori. La première Marine moderne qui saura interpréter ces données en temps réel aura un avantage décisif.

Afin d'accroître l'écart avec les forces ennemies, le concept proposé de réseau de surveillance sous-marine pourra être déployé et commander de manière furtive. Ces réseaux opèreront également avec un minimum d'intervention de la part d'un opérateur tout en exploitant à son avantage les changements environnementaux. Les résultats espérés ont le potentiel d'améliorer la capacité des capteurs et pourront changer la donne en matière de réduction d'exposition aux menaces sous-marines, d'augmentation de l'aire de surveillance, de l'accélération de la boucle OODA «observe-orient-decide-act», de minimisation d'utilisation du personnel, et de l'identification de contre-mesures rendant les sous-marins de la MRC plus furtifs.

Acknowledgements

The author would like to sincerely thank all personnel at the DRDC – Atlantic Research Centre for their continuous support. In particular, colleagues in the Underwater Sensing section and the Underwater Surveillance and Communications group have been instrumental to the success of this project.

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1 Introduction

This document reviews and summarizes the work accomplished during the three consecutive years (2013–2016) of DRDC's Adaptive Multisensor Biomimetics for Unsupervised Submarine Hunt (AMBUSH) project that was funded by a Technology Investment Fund (TIF) at the level of $750,000. In order to be self-contained, this document includes the TIF award announcement in Annex A and the original AMBUSH research proposal in Annex B. Given the body of results generated under AMBUSH, it is impossible to explicitly discuss them all at an adequate level of details. In that sense, this report constitutes an entry point and a high-level overview about the research conducted under AMBUSH as opposed to an exhaustive duplication of all results, most of which being already available in the public domain. In particular, a brief contribution summary of each significant publication figures in Annex D. Moreover, this document provides an interpretation of the derived results and a perspective about future challenges.

1.1 Review of project objectives

The undersea networks discussed here could be deployed in shallow waters and continental shelf locations with a potential ice cover. The proposed network could consist of a combination of wireless, intelligent, static sensory nodes and mobile sensory nodes, or autonomous underwater vehicles (AUV's), as illustrated in Figure 1. In this context, static nodes will provide the permanent sensor barrier whereas mobile nodes will enable the exploration of new areas, a more complete analysis of the water column, and the creation of novel network-relay communication paths.

The main objective of the AMBUSH project was to maximize the performance of persistent, undersea and wireless networked sensors made of mobile and fixed nodes through distributed, adaptive and collaborative computation performing the following tasks:

- network discovery
- network connectivity monitoring
- target localization
- adaptation to changing environmental conditions impacting the acoustic channel
- fast and opportunistic message routing

Distributed, here means the sensor-network tasks are performed collectively using contributions from multiple nodes. In this setup, each undersea sensor must develop an awareness of its surroundings so that the sensor collective behaves like an intelligent entity performing the above tasks. Distributed paradigms are usually more robust to individual node failure than their centralized counterparts. *Adaptation* is a necessary feature enabling satisfactory unsupervised behaviour. Adaptation enables network nodes to tune their collective performance in response to the dynamically changing undersea environment, which strongly influences underwater acoustic detection and communication. Similar to the wolf-pack hunting strategy,

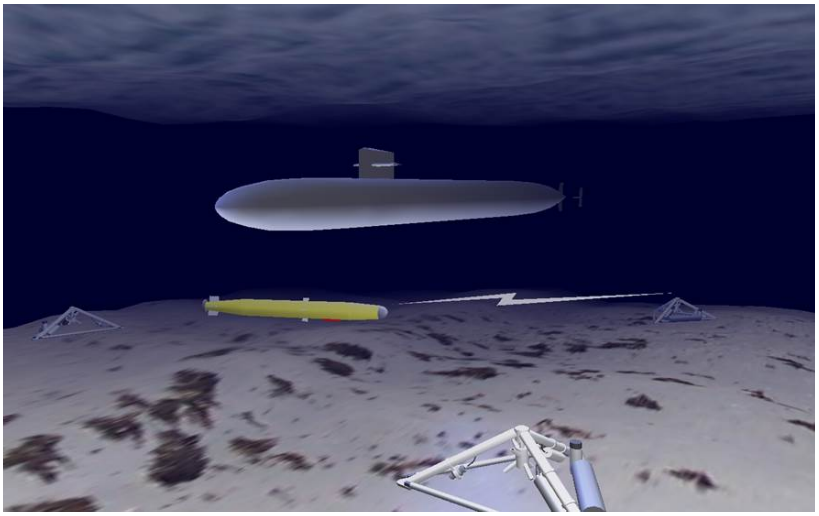


Figure 1: *Mobile and static networked sensors localizing a submarine.*

collaboration among network nodes is believed to augment the success and the robustness of their mission.

1.2 Project approach

This project adopted a sequential approach comprised of theoretical studies and simulations followed by at-sea experiments. Theoretical studies incorporated undersea-communication features while addressing the above objectives. Those studies were pursued concurrently and independently to maximize overall project success. Theoretical studies enabled the identification of performance limits in ideal conditions. Simulations helped prove concepts with fully-controlled conditions while mimicking underwater network acoustic communications and detections. Ultimately, sea-trial experiment results were used to assess prior assumptions and derive more realistic simulations.

The project execution relied on a combination of in-house, collaborative, and contracted work engaging DRDC, external contractors, and academic partners. To support the AMBUSH project, four research contracts were awarded on the following topics related to underwater acoustic sensor networks:

- network connectivity assessment (sole source – A.G. Aghdam at Concordia University)
- relaxation of distributed data aggregation (sole source – M. Rabbat at McGill University)
- robust and adaptive routing (sole source – E. Kranakis at Carleton University)
- development of an acoustic propagation simulator for shallow water environments (open-bid – Maritime Way Scientific)

Figure 2 shows the main topics being studied by the contractors listed above. When feasible, proposed solutions resulting from those research contracts were tested either experimentally

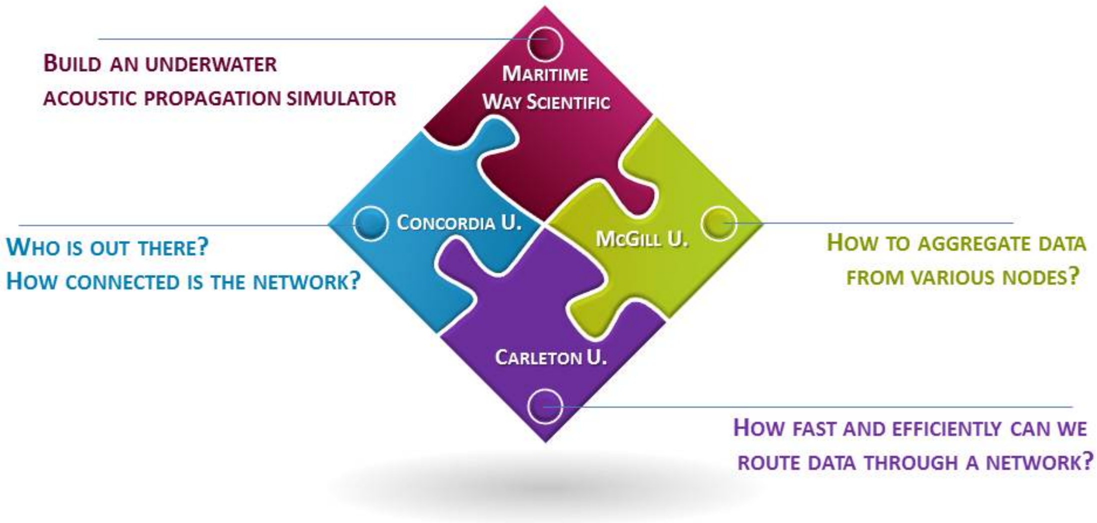


Figure 2: *Contract topics for the AMBUSH project.*

with equipment deployed in a real underwater environment or on real underwater acoustic data.

2 Results

Many achievements were accomplished throughout the life of the AMBUSH project and even though the TIF funding has ceased on March 2016, most activities continue under other projects.

Table 1 provides a succinct overview of some of those achievements where each entry in the right-most column is supported by one or many entries in the Reference section (which could not always be inserted due to space limitations). As can be seen, the AMBUSH project has impacted various military and defence groups at the national and the international levels. Just to name a few, the "International military and defence groups impacted" entry captures the international collaboration with FOI and FFI, the contribution to NATO IST-136 and the resulting invitation to join NATO ET-099, and the SPAWAR research proposal involving the author (ultimately not funded). Similarly, at the national level MP&EU requested a summary on the DIFAR sonobuoy bearing investigation, the RCN Rear-Admiral Newton requested a brief about the collaboration with Norway, and comments were requested by DGNFD Commodore A.G. McDonald.

The AMBUSH TIF has also produced a significant body of high-quality work. Among other things, the project generated: (i) prizes and awards, (ii) new sources of external funding, (iii) two new international collaborations, (iv) new university-industry collaborations, (v) many peer-reviewed publications in prestigious conferences and journal venues, and (vi) numerous invited talks, seminars and workshops. Sections 3.1 and 3.2 describe in more detail some of those impacts for the military and scientific communities.

Table 1: *Main achievements of the AMBUSH TIF project (2013–2016).*

Achievement	Number	Description
✓ National military and defence groups impacted	8	DGNFD Commodore A.G. McDonald, RCN Rear-Admiral Newton, ASW Tactics Officer, ADAC, CEJOC, CAF JAE, MP&EU, MRAS
✓ International military and defence groups impacted	11	Naval Research Lab., FOI, FFI, NATO CMRE, Gen. E.Attias (Israel), SPAWAR, Naval Postgraduate School, DARPA, NATO IST-136, ONR, TTCP
✓ Prize and award	2	Best paper [M85] Governor General Gold Medal [M86]
✓ External funding	3	OCE [G48], NRC-IRAP [G49], CAF JAE [G50]
✓ Underwater experiments	5	[H54, H55, H56, H57, H58]
✓ Requisitions/contracts	44	
✓ Internat. collaboration	2	UDNS [I59], DUSN [I60]
✓ New capability	3	Simple nodes [D34], BELLTEX [N87], DUSN underwater nodes [H58]
✓ (Under)Grad./Post-docs/ Research Associates	22	A. Ajorlou, A. Pavlov, J. Habibi, H. Mahboubi, M.M. Asadi, S. Datta Gupta, D. Ustebay, A.A. Saucan, F. Sharifi, S. Nannuru, J.Y. Yu, S. Porretta, M. Khosravi, C.W. Chao, A. Traboulsi, J. Huang, W. Wang, D. Vandenberg, J. Manuel, K. Chattopadhyay, M. Otochkina, Z. Renaud
✓ University faculty	8	M. Barbeau, E. Kranakis, M. Rabbat, M. Coates, G. Aghdam, J.F. Bousquet, G. Cervera, J. Garcia-Alfaro
✓ Peer-reviewed publications	50	Journal (7), conference (21), reports (5), research proposals (3), trial plans (5), international collaborations (2), theses (7)
✓ Other documents	53	Briefs (2), scientific letters (3), technical reports (6), NATO/TTCP (3), seminars (8), other reports (16), defence presentations (13), others (2)
✓ Industry-University collaboration	2	Carleton-MWS NSERC Engage Grant [G51], McGill-Akoostix NSERC Engage Grant [G52]

2.1 Interpretation of results

Annex D provides a brief summary of each conference proceeding and journal publication generated under AMBUSH with an overview of the main assumptions, the key conclusions, and potential avenues for future work. The present section synthesizes the content of about thirty of those publications under the following five topics: (1) author's contribution, (2) target localization, (3) network connectivity, (4) networking and acoustic communications, and (5) acoustic propagation modelling.

2.1.1 Author's contributions

The author contributed in many ways toward the various outcomes of the AMBUSH project. As the sole author of the AMBUSH research proposal (ref. Annex B), the author defined the main research topics and key assumptions that were used throughout the entire project life.

While defining the AMBUSH project, the author wrote the hardware-in-the-loop concept coupling an acoustic modem to an acoustic model propagation engine in DRDC's requisition 2012-10346, thus preceding any other scientific publication about this idea by at least 1.5-to-2 years. Such a technology is a key enabler in terms of pre-testing hardware and underwater network layouts [N87]. Also in 2012, the author's representation of an underwater sensor network by a Random Weighted Directed Graph was an innovative approach that offers many possibilities for future development [G53]. This approach continues to gain interest in the scientific community as it enables the use of Computer Science notions like directed graphs, discrete-event systems, finite-state machines, Petri nets, etc. The other novel concept proposed by the author is the use of underwater acoustic broadcasts for communicating information through a network. This broadcasting communication approach is unlike traditional hand-shaking and point-to-point communication protocols. Such a broadcast feature is advantageous from a covertness standpoint as only the broadcasting sensor node gives away its position. Moreover, reduced communication energy cost can result from such broadcasts. This last aspect is relevant to the Navy as most of its off-board sensors are powered by batteries. The proposed underwater acoustic broadcast communication technique also became a core research activity of the DUSN international collaboration with Sweden and Norway. Details about how to implement and exploit such a broadcasting scheme has been documented in [C13, C14].

The author also physically met with all members of the AMBUSH team on a regular basis to discuss progress and guide their research. As a consequence, the author's and/or AMBUSH's name figures in many university theses [O103, O104, O105, O106, O107, O108, O109] as well as in the media [P110, P111]. Those close collaborations enabled the author to become an Adjunct Professor at Carleton University and Concordia University in order to formally co-supervise graduate students and Post-Doctoral fellows. Many of the authors' ideas and concepts can be found in those theses.

In addition to the work listed above, the author developed (a) a new network discovery technique [C13], (b) a novel distributed target-localization algorithm [C15], (c) an early and comprehensive summary of findings from all groups [C16], (d) innovative localization error estimation techniques [C17, D35], and (e) an original underwater acoustic communication concept [C18].

Additionally, the author analyzed twenty years worth of sound speed profiles collected in Bedford Basin [D36] and recommended the location and orientation of Northern Watch arrays based on a formal error uncertainty analysis [D37, E39]. Each of those contribution aims at improving overall underwater sensor network performance. For instance, [C13] provides a simple algorithm enabling the discovery of a network without any prior knowledge and being robust to slow changes in the quality of communication links. In [C15], the author developed a scheme for each node to sort out their multiple bearings before transmitting to other nodes thus reducing communication overhead. Both [C17] and [D37] propose novel ways of relating sensor position and orientation to the uncertainty in target location, thus helping to resolve the network topology problem. Recently, the author also identified technology gaps in terms of autonomy and networking for a collective of underwater sensor nodes [C19].

2.1.2 Target localization

The McGill University team worked on the target localization problem [C20, C21, C22, C23, C24, B6, B7, B8]. In particular, the team mostly focused on bearing-only single-or-multiple target localization scenarios while assuming a distributed scheme where each node would perform its own target localization. For simplicity, all publications assumed the synchronization of target state updates, a data diffusion scheme like gossip, a strongly connected network of underwater sensor nodes, and a priori knowledge about the target motion model, the measurement model, and their noise characteristics. Moreover, each publication compared the proposed scheme to a more conventional and/or a centralized one.

The bulk of target localization algorithms, which include Kalman filters and Particle filters, relies on Bayes filters. In this context, a target state at time t, x_t, is comprised of the target location and speed and the main objective of the filter is to recursively identify $p(x_t|y_{1:t})$, the posterior probability density function of the target state, based on measurements up to the current time $y_{1:t}$. Bayes filtering techniques use conditional probabilities satisfying three main assumptions: (1) a target state exhibiting the Markov property (the current state value only depends on the previous state value and none of the older ones or $p(x_t|x_{t-1}, x_{t-2}, \ldots, x_1) = p(x_t|x_{t-1})$), (2) the long-time independence of observations (the current measurements at node n only depend on the previous state value and none of the older ones or $p(y_t^n|x_{t-1}, x_{t-2}, \ldots, x_1) = p(y_t^n|x_{t-1})$) as well as the node-to-node observation independence, and (3) all nodes sharing the same measurement model, target model, and noise characteristics.

The author provided many experimental datasets to the McGill University team working on target localization (Q347, NGAS2010,...). The main dataset, Q347, originates from a DRDC sea-trial and was post-processed by the author. The dataset provides a bearing-only (along with time stamps and signal-to-noise ratios) version of the real underwater acoustic data while in presence of two controlled, towed, and active sound sources. Given the nonlinear nature of the target motion as well as the non-Gaussian features of the measurement errors, a particle filtering scheme was proposed [C20]. Indeed, Kalman filters are known to perform optimally in presence of linear target motion and measurement models and Gaussian noises on those models whereas particle filters can handle nonlinear motion/measurement models and non-Gaussian noises. The main difference between Kalman and particle filters is that the latter uses a non-parametric way of representing the posterior probability density function of the target state by using a collection of particles where each particle is a potential target state value and each particle weight indicates its likelihood. Because of this approximation, usually a large number of particles ($\geq$ 1,000) is required. Another distinctive feature of particle filters is the re-sampling step which involves keeping particles with larger weights and adding new particles in a random manner.

Another challenge that the McGill team investigated was the identification of the number of targets in the scenario being analyzed through the use of Cardinalized Probability Hypothesis Density (CPHD) filters exploiting multiple sensors [C21, B7]. In particular, [C21] removed the harmful side-effect of other techniques where the node processing order affects the outcome. The work presented in [B7] extends the previous result by proposing an approximate implementation scheme whose complexity varies linearly with the network size.

The envisioned underwater sensor network would operate as follows: Acoustic detections will occur at each sensor node; when those detections match a pre-set list of features then each node will start doing beamforming to obtain a target direction-of-arrival (DOA) or bearing (multiple ones are usually obtained); to perform data aggregation then nodes would communicate their data, which would be processed by all nodes receiving those communications as they will run their own localization filter. Because of communication overhead and robustness concerns, passing all raw acoustic measurements to neighboring nodes is practically infeasible. One of two approaches could be used: either (i) each node transmits its main bearings and the receiving nodes merge those to their own bearings in order to estimate the new target state, or (ii) each node transmits its target state estimates and the receiving nodes merge those to its own bearings in order to estimate the new target state. The author performed approach (i) in [C15] while the McGill team adopted approach (ii).

Given that each underwater node must acoustically communicate the output of its target-localization or beamforming algorithm to other nodes through the unreliable and unpredictable underwater acoustic channel, the smaller the data packet to transmit is, the most likely the reception will be and the less power will be consumed. Even though broadcasting may help save power when compared to peer-to-peer communications, reducing the amount of broadcast data is key. In that sense, the McGill team worked and developed three distinct techniques to parametrize the particle cloud in a compact manner: (a) a set of six sufficient statistics [C22], (b) a clustering approach [C23], and (c) a Graph Laplacian technique [C24]. Two more practical target-localization topics were also studied: the first topic relates to the localization error when considering distributed particle filters using gossip and consensus-based algorithms [B6], and the second topic pertains to how target-localization is impacted by the Earth's curvature [B8]. As indicated in Annex D, this last topic becomes important in that the localization degenerates the further away one is from the equator and the longer the target-to-sensor distance becomes.

This work resulted in numerous noteworthy observations potentially impacting future Navy off-board sensor technologies performing target localization. First, the impact of message reception probability on localization performance has been evaluated in [C20]. It must be noted that to the authors' knowledge, this was the first time that decentralized particle filters have been carefully compared using experimental data. Secondly, the various particle cloud compact representations proposed may counterbalance the large number of particles found in particle filters, which in turns may help maintain acoustic communications power consumption at reasonable levels. Third, when using bearing-only measurements, the co-linearity of measurements due to sensor location and similar sensor perspective make the localization problem more challenging. This observation highlights how important are the sensor placement and the potential use of mobile nodes to gain distinct aspects with respect to the target. Fourth, when multiple targets are present, one must devise a scheme to associate measurements to specific target thus converting the multi-target localization problem to multiple single-target localization scenarios. Fifth, for there to be any hope of the entire network converging to a common target location, the network should have a strong enough connectivity, a topic briefly introduced in a previous section and discussed at length in the next section.

2.1.3 Network connectivity

The Concordia University team worked on the network connectivity assessment problem [C25, C26, C27, C14, C28, C29, C30, B9, B10, B11]. In particular, the team exploited the author's representation of an underwater sensor network as a Random Weighted Directed Graph in order to develop a global (network-wide) connectivity metric based on local (node-to-node) communications only. For simplicity, the first series of publications assumed that the expected communication graph of the underwater sensor network is strongly connected, which means that for any two nodes there is a communication path with a non-zero probability of existence on average (even though potentially very small at some particular time instants). The following series of publications relaxed the original assumption by requiring that the directed graph representing the network is only quasi-strongly connected. Moreover, each publication compared the proposed scheme to a more conventional and/or a centralized one. The Concordia University team also exploited a dataset generated by the author and related to underwater acoustic broadcasts [H56], which clearly showed the asymmetry[1] of acoustic communications in underwater sensor networks.

Many network functions such as data-aggregation, health-monitoring, message routing, etc. require an explicit knowledge of the network structure (or size) and topology (i.e., how each node is connected to the rest of the network). Therefore, it is important to define a global connectivity measure and develop an efficient algorithm to monitor, and if possible control, this network connectivity on a frequent basis. Although there exist various schemes for connectivity assessment in the literature, such algorithms are not distributed over the network. In this research effort, the Concordia University team developed many novel connectivity-related results including: (1) the vertex connectivity of the expected communication graph

[1] The concept of "Asymmetry" in network sciences refers to the fact that a communication link $A \to B$ (from A to B) between two network entities A and B does not guarantee that the communication link $B \to A$ exists.

[C25], (2) a joint power-and-connectivity optimization scheme [C27], (3) the weighted vertex connectivity (WVC) and approximate weighted vertex connectivity (AWVC) [C14], (4) the improved approximate weighted vertex connectivity (IAWVC) [C28], (5) the generalized algebraic connectivity (GAC) [C29], and (6) a distributed connectivity measure assessment [C30].

The joint-power optimization work in [C27] provides insights about how to minimize the total network power consumption while maintaining a lower bound on the global network connectivity for particular network topologies. All vertex connectivity metrics [C14, C28], that is WVC, AWVC, and IAWVC, seek to maintain the strongest possible connectivity by exploiting the strength of all communication links present in the network. The Weighted Vertex Connectivity (WVC) measure extends the classic notion of vertex connectivity to the more general case of random weighted digraphs. However, the NP-hard (meaning that no algorithm can terminate in polynomial-time[2]) nature of this problem requires approximations, thus explaining the necessity of AWVC, and ultimately of IAWVC that does not have the AWVC shortcomings. Coming from a totally different angle, the work presented in [C29, C30] merges the notion of connectivity to that of convergence rate for consensus-like algorithms. The proposed Generalized Algebraic Connectivity (GAC) extends Fiedler's 1973 computer science notion of algebraic connectivity for symmetric networks to the case of asymmetric networks. The new notion captures the expected asymptotic convergence rate of a family of cooperative algorithms running on such asymmetric networks. In [C30], the concept is further refined by proposing a distributed algorithm for computing the GAC from the viewpoint of each node.

The results developed by the Concordia University team can be used by the Navy for a variety of objectives such as: (1) improving the performance of an underwater acoustic sensor networks by identifying the relative contribution of each node-to-node link in the connectivity of the overall network, (2) identifying which communication link should be reinforced by either altering the acoustic modem features or the location of a mobile node such as an AUV, (3) determining the best network topology of fixed or bottom-moored nodes to guarantee network connectivity despite variations in node-to-node communication link quality, and (4) jointly managing overall network power and network connectivity.

2.1.4 Networking and acoustic communications

The Carleton University team worked on underwater acoustic communication, routing, and networking problems [C31, C32, C33, B12, O108]. In particular, the team exploited the author's knowledge of underwater acoustics and commercial acoustic modems to tackle various challenges including: (1) the coherent and incoherent modelling of underwater wideband acoustic attenuation [C31, B12], (2) a vertical routing scheme without communication void [C32] (a communication void occurs when data packets may no longer be able to move forward and toward the sink node), (3) a dynamic simulation of drifting underwater nodes

[2] The concept of "polynomial time" originates from Computer Science and captures the computational complexity of an algorithm by describing its convergence speed in relationship to its input arguments.

impacted by coloured acoustic noise [C33], and (4) an evaluation of underwater acoustic modulation schemes in Arctic-like conditions [O108].

In [C31, B12], the authors propose a series of models (both coherent and incoherent) to represent the frequency-dependent nature of underwater acoustic energy attenuation. All models are compared in an underwater acoustic communication context where the bit-error-rate (BER) in the presence of ambient noise is used as the reference metric along with a baseline case. All models share the feature of being simple and computationally fast. Coherent models generate worse BER results than incoherent ones, but are closer to experimental results when in presence of coloured noise. The proposed location-free and depth-aware routing protocol of [C32] could be applicable to underwater networks where assets are in different regions of the water column. This routing protocol considers the variability of the communication channel and comprises a recovery mode activated when the network topology changes. The work performed in [C33] combines mobility to a varying separation distance between acoustically communicating underwater nodes. For underwater operations, mobility is relevant because there are underwater vehicles and environmental conditions causing displacements of drifting and moored sensors. A combination of MATLAB and OMNeT++ codes were developed to emulate underwater acoustic digital data signal propagation, modulation, demodulation, mobility and integration of communication protocol layers.

The thesis [O108] investigated a variety of acoustic communication schemes involving phase or frequency modulations, binary/M-ary, orthogonal frequency sub-bands, single/multiple frequency carriers, and frequency-hopping. Those schemes were evaluated against a ray-tracing setup in BELLHOP with a varying ice cover and a fixed sound speed profile. In [C31, B12], the authors propose a series of models (both coherent and incoherent) to represent the frequency-dependent nature of underwater acoustic energy attenuation.

Given that most of Navy's off-board sensors are battery powered, underwater routing protocols and communication schemes must be energy-aware. In that sense, reactive routing protocols are preferred to proactive routing protocols because the latter require a constant exchange of control information to keep the routing information up to date. Given the unavailability of GPS signals under water, *location-free* routing protocols, as proposed by Carleton U., are favored as they do not require that every node knows its own and the sink node geographical positions. The inclusion of mobility in the software emulation is critical to the Navy as it enables the mixing of AUV's, drifting nodes, and moored nodes thus covering all of Navy's off-board sensor assets.

2.1.5 Acoustic propagation modelling

Given DRDC's and Navy's current budget constraints, it is advantageous to develop and test hardware, underwater communication protocols, and signal modulation schemes as much as possible in a simulated environment. The effort undertaken by Maritime Way Scientific (MWS) focused on an augmented software emulation of underwater acoustic wave propagation. Indeed, MWS augmented the ray tracing simulation technology BELLHOP by including: (1) an ice cover with realistic keel characteristics, (2) the presence of water currents, and (3) a hardware-in-the-loop feature. All of these functions are described in [N87].

Many instructive results were derived from the tool and those are fully documented in [N88, N89]. Among other things, it was found that even though water currents do not impact Doppler spread, simulations showed how a poor sampling of the water current profile can severely affect the resulting impulse response. More precisely, the arrival structure can be quite different due to various current profile samplings. It was also shown in simulations how water currents can destroy reciprocity, i.e., propagation losses from A-to-B does not equate those from B-to-A. In presence of a partial ice coverage, severe spatial banding of acoustic energy may occur. Whereas an increasing ice cover tends to increase the arrival time-spread, the number of arrivals does not seem to be too impacted for a (randomly-distributed) ice cover exceeding 25%.

All of the above-mentioned modifications of the BELLHOP ray tracer provide new capabilities to the Navy for probing the characteristics of shallow water channels. Given that the underwater surveillance technology proposed by the AMBUSH project will likely be deployed in choke-points (like narrows and straights) and in littoral waters (like the continental shelf and/or the Arctic), such a tool becomes a valuable asset to evaluate various network topologies prior to deployment.

3 National and international impacts

The next sections present some of the national/international military and scientific impacts that resulted from the AMBUSH project.

3.1 Military and defence impacts and potential applications

On the national scene, the AMBUSH project had such an impact on DRDC's and Navy's programs that its research topics became a work breakdown element (WBE 3) of the Force ASW charter [Q112] and also an important component of the Underwater Sensing and Communication (USC) group in the Underwater Sensing (US) Section. Also, the sea-trial experiments resulting from AMBUSH now benefit from an external and yearly source of funding to the level of $20K from the Canadian Armed Forces Joint Arctic Experiment (CAF JAE) at CFMWC [G50]. Also, Dr. Blouin was required by high-level executives from both DRDC and DND to provide briefs and comments on work progress [A1, A2, A3, A4, A5]. Throughout this project, Dr.Blouin influenced various DND/DRDC groups by giving oral presentations or producing documents, which include: ADAC [E40], CEJOC [E39], CAF JAE [G50], MP&EU [K66], MRAS [K67], and MAS [K68, K69]. A scientific popularization of concepts related to complex systems tailored to a military audience was also performed [Q113]. A tangible outcome of one of those activities is the DUSN (Distributed Underwater Sensor Network) international collaboration with Norway and Sweden. Another example includes the study requested by CEJOC about the impact of the spatial configuration of two seabed linear hydrophone arrays on target localization. Also, the author's comments were integrated in the final report on Maritime Systems [A1].

As a result of AMBUSH, the DRDC – Atlantic Research Centre, and thus the Royal Canadian

Navy (RCN), now have three new pieces of equipment each of which bringing new and unique experimental capabilities. The first capability pertains to BELLTEX, a modified BELLHOP ray-tracing acoustic propagation computer program, incorporating sea-ice, water current profiles, and a hardware-in-the-loop feature [N87]. The second capability relates to a series of surface nodes equipped with underwater acoustic modems and a shore radio wave link to control acoustic transmissions and acoustic modems [D34]. The third novel capability is a next-generation sub-surface underwater node comprising an acoustic modem, a vertical line-array (VLA) and a directional array (DIFAR) [H58]. Among other things, the BELLTEX tool allows (i) the testing of new hardware, (ii) Monte-Carlo studies involving variations in environmental conditions, (iii) network pre-deployment designs, and (iv) testing new modulation schemes. The simple surface node allow (v) long-term (3-to-4 weeks) testing of particular underwater acoustic modems, and (vi) remote testing of network software. The more evolved sub-surface nodes will enable (vii) testing of new on-board algorithms. Figure 3 graphically displays each of those new capabilities. At this point in time, we already received two international requests for using BELLTEX.

Other national impacts consist of new collaborations between the universities involved in AMBUSH and Canadian industries through NSERC Engage research grants between Maritime Way Scientific and Carleton University and GeoSpectrum and McGill University [G51, G52], thus leveraging the AMBUSH funding by as much as $50K. Another impact on Canadian industry was DRDC's support in testing the latest underwater acoustic recording technology [N90] and Annex C.

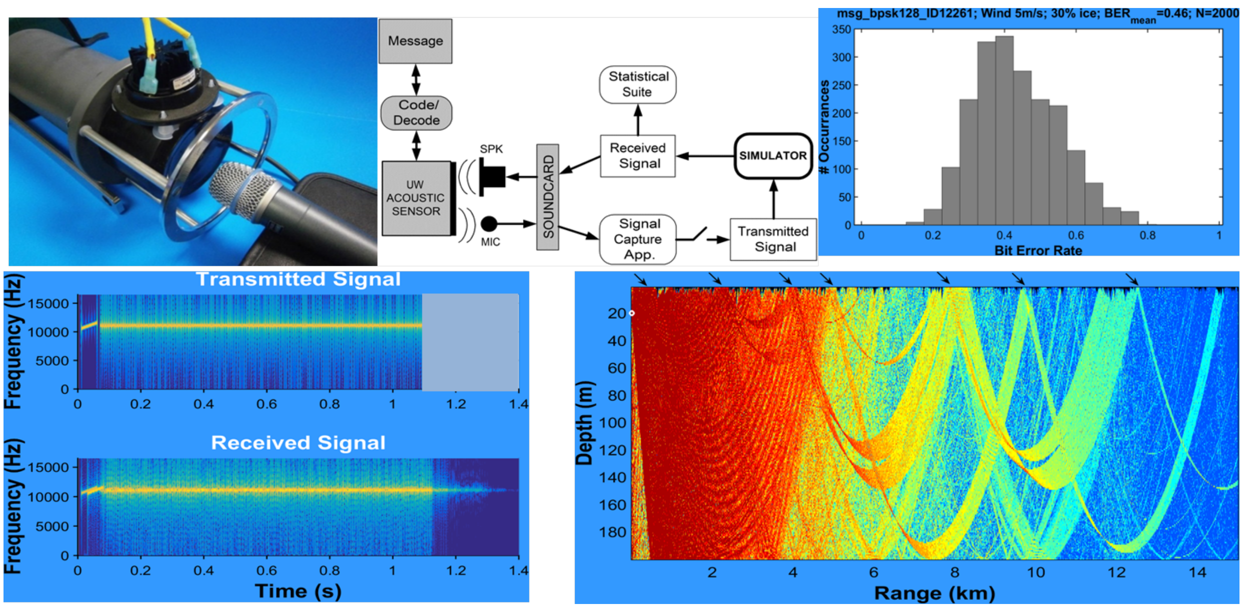
The general interest of the larger community at the Canadian Forces Maritime Warfare Centre (CFMWC) manifested itself by the large contingent of Navy officers during the AMBUSH yearly workshops held in Halifax [L77, L78].

At the international level, this project created momentum about new research fields related to underwater sensor networks. For instance, two international collaborations with national defence agencies were officially established during the AMBUSH project life. The first collaboration involves USA (ONR) and Australia (DSTO) and the second one Sweden (FOI) and Norway (FFI) [I59, I60].

Throughout this project, Dr. Blouin briefed many international military and defence agencies. These include: the Naval Research Laboratory (NRL) [K70], the Swedish defence research agency FOI [K71], an Israeli general [K72], The Technical Cooperation Program (TTCP) [J61, J62], the Space and Naval Warfare Systems Command (SPAWAR) [K73], and the Naval Postgraduate School (NPS) [K74]. Moreover, Dr.Blouin presented to various NATO groups including: the NATO Centre for Maritime Research and Experimentation (CMRE) [K75], the NATO Autonomy group [J63], and the NATO specialists panel on autonomous systems cyber-defence [J64, J65]. Recently, Dr.Blouin received a formal invitation to present to a DARPA (Defense Advanced Research Projects Agency) meeting about underwater sensor networks [K76].

(a)

(b)



(c)

__Figure 3:__ New capability: (a) surface node, (b) sub-surface node, and (c) BELLTEX.

3.2 Scientific impact

The AMBUSH project generated scientific publications, many of which were peer-reviewed, and included: (1) scientific reports [D34, D35, D36, D38, D37], (2) scientific letters [E41, E40, E39], (3) technical reports [F42, F43, F44, F45, F46, F47], (4) sea-trial experimental plans [H54, H55, H56, H57, H58], (5) contract reports [N91, N92, N93, N94, N95, N88, N96, N97, N98, N89, B6, N87, N90, N99, N100, N101, N102], (6) journal papers [B9, B6, B7, B10, B8, B12, B11], and (7) conference proceedings [C15, C13, C25, C26, C20, C16, C18, C19, C17, C27, C14, C28, C21, C22, C23, C24, C31, C32, C33, C29, C30].

This project impacted the international scientific community in many different ways. First, a portion of this research reflects the participation of eight university faculties from six different universities located in Canada, France, and Mexico.

Secondly, more than twenty students (undergraduates, graduates), Post-doctoral fellows and research associates from all origins also contributed to the project (ref. Table 1). As a result, many university theses were produced on one or many of the various topics contained by the AMBUSH project [O103, O104, O105, O106, O107, O108, O109]. Those interactions between DRDC and so many university students and faculties will have a long-lasting and beneficial effect at developing the next generation of Defence Scientists [P110].

Third, the scientific merit of the main research axes of the AMBUSH project as well as the quality of the work performed during that project were recognized by many external reviewers including: (1) The TIF external reviewer's committee [G53], the Natural Sciences and Engineering Research Council (NSERC) [G51, G52], the Ontario Centers of Excellence (OCE) [G48], the National Research Council (NRC) - Industrial Research Assistance Program (IRAP) [G49], the Governor General [M86], and a Best Paper Award to an international conference on sensor networks [M85]. Of the previous list of external reviewers, three of them (NSERC, OCE, NRC-IRAP) are research funding agencies external to DRDC.

Also, many AMBUSH members were invited all-expenses paid to present their results or give tutorials, workshops, or keynote speeches to highly-recognized international conferences [L79, L80, L81] and influential universities like Harvard University, Boston University, and NorthEastern University [L82, L83, L84].

On a broader scale, it is possible to assess the scientific impact of every peer-reviewed publication listed above in many different ways. In academia, the scientific impact of a publication is usually assessed through a combination of the main indicators, which are: (1) citations from other publications, (2) the impact factor of a journal or the acceptance rate of a conference, (3) the number of views or downloads from the editor's website, etc. For instance, since its publication in August 2015 the paper [B9] remains amongst the "Most Downloaded Systems & Control Letters Articles". That same Elsevier journal named "System & Control Letters" has an impact factor of 1.908 (as of today), which gives an averaged indication of the quality of publications found in this journal as well as how often publications from that journal gets cited. So, the higher the impact factor, the harder it is to publish in those venues. Other impact factors of publications found above are as of today the following: IEEE Transactions on Control Systems Technology (2.818), IEEE Transactions on Aerospace and Electronic Systems (1.672), and IEEE Signal Processing Letter (1.661). Certain editors, like IEEE, provides on the web the number of views/downloads and/or citations in real-time. For example, the paper [B8] that was published in 2016, already has 209 views (as of January 5 2017). Similarly, some free software like Google Scholar, Research Gate, etc. can help identify the number of citations a particular publication has. For instance, the 2013 conference paper [C13] has 14 citations in Google Scholar. Of those 13 citations, 7 originate from the same external research group that used the author's concept and extrapolated it to a new cross-correlation technique for estimating underwater network size. Obviously, all of the above-mentioned impact indicators vary in quality and over time, so the impact assessment will rarely be exact.

4 Future challenges

The ultimate and long-term endeavor of surveillance underwater wireless acoustic networks (SUWAN) is to develop insights, and ideally a software tool, for designing such networks. Such a tool could help better design underwater sensor networks by considering all important design, mission-dependent, and environmental parameters as input variables and using physics-based relationships to derive outputs being a set of range-dependent probabilistic performance measures. At an early stage, those input-to-output physics relationships may be simplistic and approximate. Closed-form solutions are preferred but iterative methods may be acceptable too. Through subsequent refinement stages, such relationships could be made more accurate. The determination of which input-to-output relationship should be refined next could be determined by analyzing the magnitude of change in the outputs following changes in the inputs through a sensitivity analysis. Once a first set of such relationships is in place, then this dynamical representation can be used to perform an overall optimization whose output would provide, if feasible, a network topology (sensor latitude, longitude, and depth) satisfying pre-defined requirements. The proposed network topology could then be evaluated numerically using a physics-based acoustic propagation simulation tool like BELLHOP to derive statistics of acoustic detections and communications.

The following list of activities captures key aspects that must be considered. This list is by no means exhaustive and will need to be refined over time as the proposed tool will most likely follow a spiral development with various improvement stages:

1. Generate and keep an up-to-date list of design, mission-dependent, and environmental input parameters.

2. Define the output performance metrics of interest. Such metrics should be probabilistic in nature and most of them should reflect a dependency with range and/or depth.

3. Start building a user interface to help drive the product development, define priorities, and manage expectations with potential military clients. The intent will be to provide early on an intermediary version providing preliminary network design solutions.

4. A literature review related to the design of SUAN as a whole or in part. Functionalities of interest for SUAN include, but are not restricted to, the following topics: distributed target detection, underwater acoustic communications, distributed target localization, distributed node localization, distributed network discovery, power management, network routing, etc. The reviewed publications should provide an algorithmic, or heuristic, or physics-based relationship relating, directly or not, a design or environmental parameter to one or many performance metrics. Some of the listed topics can be further broken down. For instance, the underwater acoustic communication topic can cover many aspects like: bit-error-rate, error-correction coding, frequency band, center frequency, modulation, redundancy, power, directionality, power consumption, message length, etc. It is recommended to initially proceed by a quick assessment of the level of effort this review will require in order to quickly come with high-level (maybe lumped) results whose details could be investigated later in a subsequent round.

5. Whenever feasible and with a minimal level of effort, validate some of the relationships derived from the previous activity through a physics-based simulation tool.

6. The following three activities borrow from a dynamic and linear single-input single output (SISO) system concept where there exists a gain relating the input and output variables. Identify the gain directionality (positive, negative, or null) of each of those input-to-output relationships and determine the constructive or destructive interactions between input and output variables. If such a gain cannot be established, then document the reasons why and propose an alternate modelling approach (such as a linearized gain, for instance).

7. Identify the relative gain differences between each of those input-to-output relationships in order to help determine which input parameters have the most significant impact.

8. Determine the absolute gain value of each input-to-output relationship.

9. Propose an event-driven high-level dynamical model representation of the network where performance metrics are the main outputs.

10. Identify to which class of optimization problems the present network design problem belongs to. Also, propose an algorithm and techniques to provide a solution to such problems.

5 Conclusions

This document briefly summarizes the various achievements of the AMBUSH TIF project from 2013 to 2016. Even though terminated at the time of writing this report, it can be claimed that the effects of AMBUSH will extend for many years to come. For instance, the international DUSN collaboration with Sweden and Norway will last until 2020. Similarly, AMBUSH-like activities are continuing under the umbrella of the Force ASW and CAUSE (Canadian Arctic Underwater Surveillance Experiment) projects at DRDC.

As a whole, the author believes that the AMBUSH project was a success for DRDC, the RCN, and the international scientific community. Indeed, the project (a) generated two international collaborations, (b) leveraged additional funding from external-to-DRDC agencies/groups thus increasing project throughput, (c) spun off new industry-university collaborations among AMBUSH team members, (d) augmented the DRDC/RCN capability toolbox with three new pieces of equipment to improve underwater surveillance, (e) involved and trained thirty (30) people (faculties, students,...) from academia on the challenges pertaining to underwater surveillance, (f) generated more than fifty (50) peer-reviewed documents, (g) influenced about twenty (20) national/international defence and military groups, and (h) created and managed over forty (40) requisitions/contracts directed toward the Canadian private and academic sectors. Based on the entries listed in the References section alone, the AMBUSH project generated on average three (3) documented entries per month for the entire 36-month life-period of the project.

All of the above-mentioned achievements depict a collective effort that the author had the pleasure and the opportunity to orchestrate. Not only as the TIF funding for the AMBUSH project helped generate new results, it propelled DRDC at the forefront of a nascent, challenging, and exciting research field. The author sincerely thanks all of those who were involved, directly or indirectly, with the AMBUSH project and hopefully this report adequately depicts their contribution.

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Annex A: Announcement of TIF award

National Defence
Assistant Deputy Minister
(Science & Technology)
National Defence Headquarters
Ottawa, Ontario
K1A 0K2

Défense nationale
Sous-ministre adjoint
(Science & technologie)
Quartier général de la Défense nationale
Ottawa (Ontario)
K1A 0K2

7000-25-1 (OCS)

Le 12 février 2013

M. Blouin,
R & D pour la defense Canada - Atlantique
9 Rue Grove
Dartmouth, Nouvelle-Écosse
B2Y 3Z7

Cher Monsieur Stéphane Blouin,

Je vous remercie de l'excellent effort que vous et votre équipe avez déployé lors de la préparation du projet de recherche intitulé "Adaptive Multi-sensor Biomimetics for Unsupervised Submarine Hunt (AMBUSH), " pour le programme Fonds d'investissement technologique (FIT).

Le programme FIT est très bien coté pour la promotion des recherches d'avant-garde du programme de R & D pour la défense. Le succès de ce programme repose entièrement sur la détermination et l'expertise d'équipes telles que la vôtre.

Dans ce cycle, 16 propositions ont été soumises à l'évaluation du comité de sélection des projets du FIT. Elles ont été examinées par des experts internes et externes qui les ont cotées pour la qualité scientifique, la nouveauté, le développement des capacités, l'impact, le risque, et enfin, pour leur alignement aux objectifs de l'organisation. Elles étaient toutes de haute qualité, et nous n`avons pu en financer que trois. Votre projet a reçu une cote très élevée, et je suis heureux de vous annoncer que le CERD a accepté de le financer au niveau de $750 K.

Si vous avez des questions concernant le processus de sélection ou des commentaires particuliers sur la façon d'améliorer le programme du FIT, je vous recommande de vous adresser au Scientifique en chef de votre centre.

Je vous remercie de votre participation au programme FIT et vous prie d'agréer, cher Monsieur, mes salutations distinguées.

Marc Fortin

M Blouin
DRDC - RDDC
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SCANNED INTO DMCS
MAR 0 8 2013
FILE NO. 7000-1
Computer PA Actioned
(Init.) (Date) 08 Mar 13

Canada

Annex B: Original TIF proposal

2012 TECHNOLOGY INVESTMENT FUND (TIF) PROJECT PROPOSAL

1. Basic Information

Project Title: Adaptive Multi-sensor Biomimetics for Unsupervised Submarine Hunt (AMBUSH)		**Date:** 2012-07-02
Principal Investigator: Stéphane Blouin **Centre:** DRDC Atlantic	**E-mail:** stephane.blouin@drdc-rddc.gc.ca **Partner Group:** PG-1 Maritime **Thrust:** 11c – Underwater (UW) Warfare **Primary S&T Expertise:** 03-ISR – Underwater Warfare and Surveillance	**Telephone:** 902 426-3100 x216 **Fax:** 902 426-9654
Project Team Members: **1.** Dr. S. Blouin† DS-4 **2.** Dr. G.J. Heard* DS-6 **3.** Dr. C.A. Rabbath† DS-4 **4.** Dr. A.G. Aghdam **5.** Dr. M. Rabbat **6.** Dr. E. Kranakis **7.** LCdr J. Collins * = Group Leader, † = Adj. Faculty	**Affiliation:** **1.** DRDC Atlantic, UW Surv. & Comms **2.** DRDC Atlantic, UW Surv. & Comms **3.** DRDC Valcartier, Precision Weapons **4.** Concordia U., Elec. & Comp. Eng. **5.** McGill U., Elec. & Comp. Eng. **6.** Carleton U., Computer Science **7.** CFMWC, ASW Tactics Officer	**Fiscal Year:** 13/14 start

1a. Abstract: (Suitable for Publication, 150 words maximum)

Underwater surveillance is inherently difficult because data transmission is limited and unpredictable when moving targets and sensors evolve in the communication-opaque undersea environment.

This proposal finds inspiration in nature's collaborative tasks, such as wolves hunting in packs, to advance undersea-surveillance. Much like hunting wolves combining pre-learned behaviour and infrequent communications, this proposal combines decentralized data-aggregation with nature-inspired adaptation. This approach could augment sensors capability and enable game-changing collaborations that could reduce threat exposure, increase coverage, minimize operator intervention, and improve covertness, among other things.

There is mounting evidence of successful implementation of bio-inspired techniques, but current research efforts do not focus on underwater challenges. Experimental research typically reduces to short-range and full-connectivity, while theoretical research usually assumes unrealistic communication-pathways. However, recent advances in sensor computational capability, underwater network protocols, and bio-robotics have enabled a paradigm-shift that will help leverage two unique undersea features: intermittent communication and dynamic environmental changes.

2. General Description of Proposed Project (2 page maximum)

OVERVIEW Unmanned systems and off-board sensors are becoming a critical part of the Canadian Forces (CF) toolbox to keep troops out of harm's way [1,2,3], but automated data aggregation is needed to reduce analysis overhead. Recent demonstrations of the network-centric warfare revealed the advantages of networked collaborations [4,5]. This project combines similar automation and collaboration ideas for unsupervised undersea-surveillance where sensors will display nature-like collaborative and adaptive behaviours, as those observed in wolves hunting in packs. From a military standpoint, this concept could bring improvements at the operational, tactical, and maybe strategic level. Mainstream research has derived partial answers for enforcing collaboration on terrestrial or aerial networks but, to this day, there has been no implementation of a collaborative and adaptive wireless undersea sensor-network. The proposed research presents a formidable scientific challenge, with proportional rewards, and promising security and defence applications.

BACKGROUND One of the simplest network-collaborative tasks amounts to nodes trying to agree on a common value of interest [6,7,8]. Recent results in the literature describe how such an agreement can be guaranteed based on various network configurations [9,10,11,12,13]. Collaborative tasks also occur in nature within and between species [14,15,16,17,18]. For instance, a hunting wolf pack relies on an elaborate language to improve hunting success. Through biomimetics, researchers have implemented collaborative hunting behaviours in terrestrial and aerial robots [19,20,21]. Our challenge is to apply these concepts to the undersea environment where wireless communications are very difficult due to propagation losses, multi-path interference, large propagation delays, and unpredictable attenuations [22].

Experimental underwater-sensor research often reduces to short-range setups preserving full-connectivity [23,24,25]. But a hunting wolf pack is not always communicating which demonstrates that collaboration is possible with intermittent communication. Recent simulation results indicate that inter-wolf communication is less frequently tapped into than the use of pre-learned behaviours [17]. Social insects such as ants, termites and bees living in colonies also show that a high level of collaboration can be achieved with limited computational capability [26]. These facts suggest that undersea sensor-networks may be able to increase performance over greater distances by collaborating through intermittent communication while exploiting their limited in-sensor computation capability. Unlike the wolf pack strategy used by U-boats in WWII, we envision here that execution and command will be decentralized at the sensor level with a possibility of altering missions when the undersea sensor-network will surface to report a potential target of interest.

The main roadblock for exploiting the collaboration potential is due to a lack of theoretical research on networked-sensor data aggregation focusing on the underwater environment. Terrestrial research studies often assume that the entire network structure is known by every node, thus requiring frequent communication and a centralized knowledge center [27,28,29]. There are numerous results on decentralized approaches showing promise for military and civilian purposes, such as weapon-target assignments and common operational pictures [30,31,32,33,34,35,36,37,38,39,40,41,42,43]. But these publications often assume bidirectional [7], instantaneous multi-hop [13], or peer-to-peer [9] links, whereas undersea communications are often unidirectional and of the broadcast type with strong variability. Unlike these results, this research will offer a *collaborative*, *adaptive* and *decentralized* technology tailored to undersea environments.

PURPOSE Military undersea-surveillance networks usually are wired, deployed overtly in friendly waters, and requiring a significant operator/analyst overhead. As a coalition member, the Royal Canadian Navy is often tasked to patrol or secure strategic choke points with a small number of warships and away from friendly waters. These situations keep Navy personnel and assets within the reach of an opposing force, thus requiring a high-level of readiness over long periods of time. For maximal protection, the Navy should be able to deploy and operate an undersea-surveillance network in a covert manner to increase its standoff distance. For optimal operational effect, such an undersea-network must also be able to operate in an unsupervised mode while exploiting the changing undersea environment to its advantage.

Much like hunting wolves favoring visual rather than vocal communication for covertness, this research proposes an unsupervised surveillance concept maximizing target localization and sensor covertness. In addition to the knowledge gained, this project, if successful, could help reduce threat exposure and operator intervention, increase standoff distance and sensors' coverage, and accelerate target localization, among other things. The project high payoffs are counterbalanced by the high risks of this leading-edge research. Indeed, both theoretical and practical limitations are yet unknown and the failure of any of the major tasks could significantly compromise the effectiveness of the overall outcome. This proposal aligns with many Department of National Defence (DND) technological documents [A,B,C] highlighting the needs for better automation, sensor information management, data aggregation, and networks. The early involvement of LCdr Collins will ensure that critical warfare mission aspects are met by this project.

SCIENTIFIC AND TECHNICAL OBJECTIVES **Overall Objective** This proposal aims at maximizing the impact of current and future CF undersea assets by enabling game-changing collaborative and adaptive behaviours amongst undersea-surveillance networked sensors. **Assumptions** The proposal assumes the existence of: (i) programmable undersea sensors with sufficient computational capacity, and (ii) an operational undersea network communication protocol. Recent advances listed below indicate that these assumptions are reasonable; therefore the bulk of the risks lies in the following hypothesis. **Hypothesis** Collaboration and adaptation among undersea networked-sensors can occur in a stable, predictable, and unsupervised manner for detecting and localizing moving targets. **Scientific Objective** The primary scientific objective is to *investigate the conditions guaranteeing stable, collaborative, and adaptive tasks for undersea networked sensors subject to unpredictable communications and tasked to localize a target*. The following unresolved technical goals are needed to achieve the scientific objective:

(a) Identification of suitable collaborative and adaptive behaviours for a combination of fixed and mobile sensors;
(b) Self-learning of the number of network nodes and analysis of its impact on collaboration;
(c) Local monitoring of network connectivity and identification of necessary communication links;
(d) Minimization of the impact of network time delays/latencies and packet drops;
(e) Estimation of other node's state value and its impact on collaboration; and
(f) Maintenance of collaboration stability with above features (b)-(e) all present.

The failure to succeed at any of the above technical goals could significantly reduce the project impacts.
Probability of Success We believe nature's powerful collaborations with limited communications and computation provide examples from which we can learn how to enable collaborative behaviours amongst networked sensors. This belief is reinforced by three recent advances: (1) Communication Research Center Canada (CRC) is currently developing an undersea network protocol [44] and DRDC has recently implemented the US Seaweb technology in undersea sensor nodes [45], (2) in-sensor computational capability will continue to increase over the years [46] and the DRDC Starfish networked sensors now have on-board computational capability, and (3) the field of bio-robotics has experienced significant recent breakthroughs. For example, a humanoid robot can now walk despite being kicked and bumped [47,48]. Similarly, robotic fish can adapt their physical features through evolutionary computation while evolving in an aquatic environment [49]. These results demonstrate the rapid advance of adaptive technologies.

APPROACH & METHODS **Approach** This proposal adopts a sequential approach comprised of theoretical studies, simulations, and experiments. Theoretical studies will incorporate undersea-communication features while addressing the technical goals (a)-(f) presented earlier. Most of these goals will be pursued concurrently and independently for maximizing the project overall success. The project execution will rely on a combination of in-house, collaborative and contracted work engaging DRDC centres and academic partners. The latter will help build in-house capabilities during project years 1&2. In project year 3, a progressive migration towards experiments will occur. In-house contributions will amount to theoretical development performed by the principal investigator and experimental research supported by other DRDC centers. **Methods for Theoretical Work** Much like wolves combining pre-learned behaviour and infrequent communications, this proposal will combine decentralized data-aggregation with adaptive and collaborative features inspired by nature. For data-aggregation, we intend to model dynamic network topologies through time-varying directed graphs [50]. Moreover, the project will deliver discrete-time solutions for computer implementation. **Technical Goals** Technical goal (a) will identify subtle collaborative and adaptive behaviours required for undersea surveillance missions. For technical goal (b), the intention is to extend recent results from computer science [40]. Goal (c) requires a connectivity metric analogous to that of [42] but decentralized [53]. A good starting point for goal (d) will be to model delays and packet losses as varying data trustworthiness [36,54,55]. Goal (e) will attempt to augment the approach of [31] for scenarios with disrupted communications. To address goal (f), we will need to properly manage compromises arising from the solutions of technical goals (a)-(e). Model-free adaptive techniques [49,51,52] are preferred as they provide adaptability to unforeseen situations and simpler implementations compared to model-based adaptive approaches. For robustness reasons, all above techniques will have decentralized data processing. **Methods for Experimental Work** Since simulations are used initially to assess success, CF and DRDC personnel will engage early on to capture relevant military-mission network features. Validation through experiments will be performed in two steps: a safer first step in a lab followed by a riskier step involving DRDC Atlantic AUV's [56] and sensors. Experiments will rely on the undersea network protocol being developed by CRC and/or the US Seaweb code.

RISK MITIGATION & PRELIMINARY DATA The "Project Work Plan" contains risk attenuation measures with some contingencies providing acceptable alternative routes and others potentially leading to an overall decrease in performance. Despite potential performance losses, an improved effectiveness of today's undersea sensing technology will still be achievable. The highest identified risks are (*mitigation measures in italics*): (A) Theory or simulations result into weak collaboration capabilities when the network knowledge is decentralized (*This issue should surface prior to the project mid-life. At that point the team could opt for a partial decentralization or a fixed network connectivity.)*, (B) Real-time implementation is computationally taxing (*This risk should be identified early through project reviews and algorithm testing. This risk may require code simplification and optimization or simply a feature reduction).* Other than the embryonic results from the principal investigator [35,36,37], no preliminary data on such undersea networks is available in the public domain. The probability of success is addressed in "Scientific and Technical Objectives".

3. Rationale for Choice of External Partner **(¼ page maximum)**

This proposal requires university faculties for addressing fundamental issues in a timely manner. DRDC scientists do not currently possess the skills for executing this proposal and a single DRDC scientist would need about 10 man-years for developing this proof of concept. The relative proximity of university faculties will facilitate project execution.

People's expertise complements each other. The university faculty team provides expertise in Consensus/Gossip [32,57], Distributed Computation [33,58], Optimization [34], Learning [40], Control [31], Networks [28], and Graphs [12], all of which are needed skills for this project. Dr. Rabbat has conducted research on distributed algorithms with applications to sensor networks and information fusion. His involvement with the McGill Computer Networks Research Lab will bring transformative ideas. Dr. Kranakis is a world recognized authority in network-related topics. His prolific research shows the synergy between computer science and mathematics, with both fields being required for this project. Dr. Aghdam, a Full Professor, is a leading authority in multi-agent, adaptive switching, and sampled systems that are all highly relevant.

The proposed university faculty team already advised the principal investigator on past funding and research endeavours [D,E]. The principal investigator experience at commercializing new technologies combined to the experimental field experience of other DRDC team members nicely complement the theoretical profile of the external collaborators. DRDC will also actively engage into the theoretical, practical and experimental portion of this project.

4. Project Work Plan

Activity Phase	Description	Resources Needed ($K, PYs)	Milestones
1. Preparation Work *Lead:* S.Blouin, G.J. Heard *Objectives:* 1) Planning and scoping ahead of time so that research efforts starts as early as possible with funding availability. 2) Define the mission space of collaborative networked operations and their requirements. 3) Define experiments.4) Identify simulation requirements. 5) Define success metrics and performance baseline. *Timeline:* Months separating confirmation of TIF support and new fiscal year *Risk Mitigation:* By preparing contracts or standing offers ahead of time, we reduce the risk of a late start.	**1.1 Detailed scope (main points)** Define current deficiencies and future challenges/needs for networked operations in underwater warfare scenarios. Identify military-relevant collaborative and adaptive behaviours (Technical Goal (a)) Provide a solution vision (impact on current practice, baseline, deliverables, etc.). Define details of final experiment with fixed and mobile sensors so that it captures features of relevant CF missions (comm. delays, dropouts, etc.) and available sensors. Define intermediate lab experiments in line with final experiment. **1.2 Identification of Experiment Features & Requirements** Investigate and document all lab, experimentation, and implementation requirements (programming language ...) and constraints (CPU, memory, disturbances, etc.). Make sure simulation and experimental features line up to ensure proper proof-of-concept validation and smooth transition from simulation to experiments. Assess effort for developing simulation environment and determine a list of features so that contractors can commonly develop a simulation test-bed. **1.3 Contracts Preparation** Use documents 1.1 and 1.2 to write up contracts and work out assignments with timeline.	**Subtotals** 0.2 PY DRDC A 0.05 CFMWC 0.05 PY DRDC V 0.05 PY Carleton U. (in-kind) 0.05 PY Conc.U. (in-kind) 0.05 PY McGill U. (in-kind) **Legend:** DRDC A = Atlantic DRDC V = Valcartier PY = person-year **Total** **0.25 PY DRDC** **0.15 PY in-kind**	**1.1** Scope document with: - Top mission scenarios involving adaptive collaboration through networks. Operational requirements of top mission scenarios - Project tasks definition re-usable for R&D contracts. - List of collectively agreed upon deliverables. - Set of success metrics and performance baseline connected to mission scenarios. - Details of lab and final experiments. **1.2** Document containing key features and requirements for building simulation environment. **1.3** Contracts ready for beginning of new fiscal year
2. TIF granted *Lead:* S.Blouin	**2.1 Put R&D contracts in place** **2.2 Prepare and conduct kick-off meeting** (teleconference)	**Sub-totals** 0.05 PY DRDC A **Total** **0.05 PY DRDC**	**2.1** Activated R&D contracts.

3. Preliminary Work *Lead:* S.Blouin, G.J. Heard *Objectives:* 1) To update knowledge base with most recent results. 2) To formalize problem statement in mathematical terms. 3) To guarantee integration of the various technical goals and alignment with relevant CF missions (current & future) *Timeline:* Q1Y1 *Risk Mitigation:* To reduce failure risks we intend to explore many techniques (Consensus, Gossip, etc.). If all fail, we will need to retain centralization in certain nodes which may or may not be acceptable from a practical standpoint.	**3.1 State-of-the-art** Review and analyze latest decentralized data aggregation results and update plan if major theoretical breakthrough occurred. [$25K TIF for R&D contracts] Review/analyze latest results on adaptive approaches and self-learning techniques. Update project plan if breakthroughs occurred. [$25K TIF for R&D contracts] **3.2 Selection of Aggregation Form** Given requirements identified in Activity 1 evaluate which data aggregation form is appropriate. [$15K TIF for R&D contracts] **3.3 Detailed Problem Statement & Constraints** Given requirements identified in Activity 1 as well as reviews 3.1 formalize a detailed problem statement with constraints, identify mathematical modeling framework. [$15K TIF for R&D contracts] **3.4 First face-to-face meeting** Make sure everybody agrees with the problem statement. Discuss the detailed work breakdown including the common simulation platform and the experimental plan. [$5K TIF for travel costs]	**Sub-totals** 0.2 PY DRDC A 0.05 PY DRDC V 0.05 CFMWC $5K DRDC O&M, TIF Funds $80K TIF for R&D contracts 0.05 PY Carleton U. (in-kind) 0.05 PY Conc.U. (in-kind) 0.05 PY McGill U. (in-kind) **Total** **0.25 PY DRDC** **0.15 PY in-kind** **$85K**	**3.1** Literature reviews: Two publications, i.e., conference, journal and/or Technical Memorandums (TM's) by end of Q1Y1. **3.2** Aggregation type selected to match CF requirements. **3.3** Formal problem statement and modeling paradigm defined. **3.4** A common understanding of the project's problem, goals, and practical design space and risk mitigation for misunderstanding the project attributes.
4. Network Structure Learning (Technical Goal (b)) *Lead:* E. Kranakis ,S.Blouin *Objectives:* 1) Develop self-learning algorithms to determine the network structure. 2) Manage varying network size. 3) Assess the impact of the algorithm(s) on data aggregation.	**4.1** Evaluate most appropriate techniques for estimating network structure in real-time. Build corresponding algorithm. Simulate and study the convergence rate to the true network structure based on communication topologies. [$25K TIF for R&D contracts ,Q1Y1] **4.2** Develop a technique for managing data aggregation dimensionality changes due to unknown network structure. Generalization of previous results to cases with communication delays and dropouts. [$25K TIF for R&D contracts ,Q3Y1]	**Subtotals** **Y1** 0.15 PY DRDC A $50K TIF for R&D contracts $2.5K DRDC O&M, TIF Funds 0.05 PY Carleton U. (in-kind)	**4.1** A scientific foundation for selecting the most appropriate self-learning algorithm to accommodate relevant CF missions identified in Activity 1. **4.2** A practical means to compensate for the data aggregation dimensionality change.

4. Network Structure Learning (continued) (Technical Goal (b)) *Timeline:* Q1Y1 ⇒ Q2Y2 *Risk Mitigation:* If too slow, we may have to consider sub-network data aggregation and its associated implications.	**4.3** Proof of finite computation time of the proposed algorithm(s), or identify necessary changes to attain it. [$15K TIF for R&D contracts ,Q2Y2] **4.4** Perform overall simulation tests, assess performance, and analyze CPU and memory requirements. [$15K TIF for R&D contracts,Q2Y2]	**Subtotals** **Y2** 0.15 PY DRDC A $30K TIF for R&D contracts $2.5K DRDC O&M, TIF Funds 0.05 PY. Carleton U. (in-kind) **Total** **0.3 PY DRDC** **0.1 PY in-kind** **$85K**	**4.3** Evidence of the algorithm performance and computational intensity. **4.4** Implementable and functional algorithms self-learning a network structure. Yearly summary due by Q4Y1. Publications summarizing the results (conference, journal, and/or TM) by end of Q2Y2.
5. Network Connectivity (Technical Goal (c)) *Leads:* A.G. Aghdam, E.Kranakis, S.Blouin *Objectives:* 1) Develop local network connectivity metric. 2) Determine a control strategy for stable aggregation. 3) Assess the impact of the algorithm(s). *Timeline:* Q1Y1 ⇒ Q2Y2 *Risk Mitigation:* In case of failure, we may need to consider a global connectivity metric. A major decision point and performance impact element.	**5.1** Develop connectivity metric for data aggregation stabilization. Monitor the metric and study its behaviour through simulations. [$25K TIF for R&D contracts,Q2Y1] **5.2** Identify necessary & sufficient conditions for a stable aggregation. [$25K TIF for R&D contracts,Q3Y1] **5.3** Define a connectivity control mechanism enabling or enhancing aggregation stabilization. [$20K TIF for R&D contracts,Q4Y1] **5.4** Generalize previous results to a scenario with a variable # of network nodes, communication delays & dropouts, and state value estimation. [$20K TIF for R&D contracts,Q2Y2] **5.5** Proof of finite computation time of the proposed algorithm. Perform overall simulation tests, assess performance, and analyze CPU and memory requirements. [$10K TIF for R&D contracts,Q2Y2]	**Subtotals** **Y1** 0.15 PY DRDC A $70K TIF for R&D contracts $2.5K DRDC O&M, TIF Funds 0.1 PY Conc. U. (in-kind) 0.1 PY Carleton. U. (in-kind) **Y2** 0.15 PY DRDC A $30K TIF for R&D contracts $2.5K DRDC O&M, TIF Funds 0.05 PY Conc. U.(in-kind) **Total** **0.3 PY DRDC** **0.25 in-kind** **$105K**	**5.1** A local connectivity concept and a computational method applicable to collaborative networks. **5.2-5.5** Theoretical evidences of the algorithm fundamental requirements. Practical evidences of the algorithm performance and computation intensity. **5.5** A first version of implementable and functional algorithms for monitoring and controlling network connectivity for a cooperation objective. Yearly summary report due by end of Q4Y1. Publication(s) summarizing the results (conference, journal, and/or TM) by end of Q2Y2.
6. Delays and Dropouts (Technical Goal (d)) *Lead:* C.A. Rabbath, M. Rabbat, S.Blouin	**6.1** Determine a way to model delays and packet dropouts so that it can blend with modelling techniques used to solve other technical goals. [$25K TIF for R&D contracts,Q1Y1] **6.2** Study the impact of delays and dropouts on aggregation and determine threshold values de-stabilization. [$25K TIF for R&D contracts,Q2Y1]	**Subtotals** **Y1** 0.15 PY DRDC A 0.05 PY DRDC V $75K TIF for R&D contracts $2.5K DRDC O&M, TIF Funds 0.1 PY McGill U.(in-kind)	**6.1-6.2** Clear and documented understanding of the impact of communication delays and dropouts on collaboration. Integrated representation of delays and dropouts in accordance to the problem statement framework developed in Activity 3.

6. Delays and Dropouts (continued) (Technical Goal (d)) *Objectives:* 1) Investigate delay and dropout effects. 2) Develop techniques minimizing their impact. 3) Assess the proposed algorithm(s). *Timeline:* Q1Y1 ⇒ Q2Y2 *Risk Mitigation:* If everything fails, we can drop data that is too old or too corrupted, a costly solution.	**6.3** Explore the possibility of predict-ting time delays packet dropouts for minimizing their effects. Design algorithms and test performance. [$15K TIF for R&D contracts,Q3Y1] **6.4** Generalization of all previous tasks to a variable # of network nodes, dynamic connectivity, and state value estimation. [$10K TIF for R&D contracts, Q4Y1, $10K TIF for R&D contracts,Q1Y2] **6.5** Proof of finite computation time of the proposed algorithm, or identify necessary changes to attain it. Perform overall simulation tests, assess performance, and analyze CPU and memory requirements. [$20K TIF for R&D contracts,Q2Y2]	**Subtotals** **Y2** 0.15 PY DRDC A 0.05 PY DRDC V $30K TIF for R&D contracts $2.5K DRDC O&M, TIF Funds 0.05 PY McGill U. (in-kind) **Total** **0.4 PY DRDC** **0.15 PY in-kind** **$110K**	**6.2-6.4** Knowledge of the effectiveness of an estimation technique to reduce delay and dropout impacts. **6.5** A first version of implementable and functional algorithms for reducing delay and dropout impacts on collaborative tasks. Yearly summary report due by end of Q4Y1. Publication(s) summarizing the results (conference, journal, and/or TM) by end of Q2Y2.
7. State Estimation (Technical Goal (e)) *Lead:* M. Rabbat, A.G. Agdham, S.Blouin *Objectives:* 1) Develop a state estimation algorithm(s). 2) Investigate control techniques minimizing the impact of slow state estimation. 3) Assess the proposed algorithm(s). *Timeline:* Q1Y1 ⇒ Q2Y2 *Risk Mitigation:* In case of failure, nodes may need to pass around extra information about other nodes. A second significant decision point and performance impact element.	**7.1** Select an approach estimating the network state vector and/or by passing around other nodes' information. Determine self-tuning properties and conditions when the estimation converges. [$25K TIF for R&D contracts,Q2Y1] **7.2** Based on outcomes from Activity 7.1 assess the impact of state estimation speed on aggregation stabilization. [$20K TIF for R&D contracts,Q3Y1] **7.3** Study how a controlled activation of certain comm. links improves the state estimate. Build and test an algorithm enforcing such control. [$25K TIF for R&D contracts,Q4Y1] **7.4** Generalization of previous task to a scenario with a variable # of network nodes, comm. delays & dropouts, and dynamic connectivity. [$25K TIF for R&D contracts,Q2Y2] **7.5** Proof of finite computation time of the proposed algorithm, or identify necessary changes to attain it. Perform overall simulation tests, assess performance, and analyze CPU and memory requirements. [$15K TIF for R&D contracts,Q2Y2]	**Subtotals** **Y1** 0.15 PY DRDC A $70K TIF for R&D contracts $2.5K DRDC O&M, TIF Funds 0.1 PY Mcgill U. (in-kind) 0.1 PY Conc.U. (in-kind) **Y2** 0.15 PY DRDC A $40K TIF for R&D contracts $2.5K DRDC O&M, TIF Funds 0.05 PY McGill U.(in-kind) 0.05 PY Conc.U. (in-kind) **Total** **0.3 PY DRDC** **0.3 PY in-kind** **$115K**	**7.1** A state estimation technique with good convergence properties and that does not require human intervention. **7.2-7.4** A clear understanding of the impact of a slow state estimator on aggregation stability and a technique for minimizing it. **7.5** A first version of implementable and functional algorithms for estimating network state values in cooperative tasks over ad hoc networks. Yearly summary report due by end of Q4Y1.Publication(s) summarizing the results (conference, journal, and/or TM) by end of Q2Y2.

8. Collaboration stability (Technical Goal (f)) *Lead :* A.G. Agdham, M.Rabbat, E. Kranakis, *Objectives:* 1) Assess the integration of individual results and algorithms. 2) Develop an adequate approach to solve the overall aggregation problem. 3) Simulate all solution algorithms for technical goals (a)-(e). 4) Determine experimental readiness. *Timeline:* Q3Y2 ⇒ Q4Y2	**8.1** Assess results readiness for Activity 4, 5, 6, and 7. Analyze individual outcome and tradeoffs. [$25K TIF for R&D contracts,Q3Y2] **8.2** Identify a feasibility region satisfying all constraints. [$25K TIF for R&D contracts,Q3Y2] **8.3** Determine if overall system and operating conditions fit a classic type of dynamic programming problem and identify options available to solve it (we expect the first step to fail). [$25K TIF for R&D contracts,Q3Y2] **8.4** Given that all conditions from Activity 4, 5, 6, and 7 apply, identify overall necessary & sufficient conditions for stable aggregation. [$35K TIF for R&D contracts,Q4Y2] **8.5** Perform overall simulation tests, assess performance, and analyze CPU and memory requirements. [$40K TIF for R&D contracts,Q4Y2] **8.6** Perform an overall project review and group meeting to determine the readiness for a laboratory experiment. [$20K TIF for R&D contracts]	**Subtotals** 0.3 PY DRDC A $170K TIF for R&D contracts $10K DRDC O&M, TIF Funds 0.05 PY McGill U. (in-kind) 0.05 PY Conc. U. (in-kind) 0.05 PY Carleton U. (in-kind) **Total** **0.3 PY DRDC** **0.15 PY in-kind** **$180K**	**8.1** Major project milestone indicating if the overall concept is, in principle, implementable (in fact progress will be tracked over Y1 and Y2 to mitigate any significant and detrimental finding). **8.2-8.3** Configuration of the real-time optimization problem. **8.4-8.5** Theoretical and practical evidences of the correctness of past efforts. First version of an overall set of algorithms enforcing technical goals (a)-(e). **8.6** Other major milestone assessing how confident the team is regarding the next experimental tests in a laboratory. Project summary report and publication(s) summarizing the results (conference, journal, and/or TM) by end of Q4Y2. A list of lessons learned and counter measures collected during the project.
9. Experiments *Lead:* S.Blouin *Timeline:* Q1Y3 ⇒ Q4Y3	**9.1** Lab experiments [$35K TIF for R&D contracts,Q1Y3] **9.2** At-sea experiments (see Section 5.a for details) [$35K TIF for R&D contracts,Q3Y3]	**Total** **0.6 PY DRDC** **$70K**	**9.1-9.2** Technical knowledge for the deployment and the operation of an unsupervised, collaborative, and adaptive undersea-surveillance sensor-network.

Timing of Resources for Main Tasks

People	Affiliation	Overall List of Activiities									Total FTE [in-kind]
		Preparation Work + T.Goal (a)	Preliminary Work	T.Goal (b)	T. Goal (c)	T.Goal (d)	T.Goal (e)	T.Goal (f)	Laboraty Experiments	Final Experiment	
S Blouin	DRDC A	0.15	0.15	0.3	0.3	0.3	0.3	0.3	0.3	0.3	2.4
G.J. Heard	DRDC A	0.05	0.05						0.05	0.05	0.2
C A Rabbath	DRDC V	0.05	0.05			0.1					0.2
M. Rabbat	McGill U.	0.05	0.05			0.15	0.15	0.05	0.01	0.01	0.5
E. Kranakis	Carleton U.	0.05	0.05	0.1	0.1			0.05	0.01	0.01	0.4
A G Aghdam	Concordia U.	0.05	0.05		0.15		0.15	0.05	0.01	0.01	0.5
J. Collins	CFMWC	0.05	0.05								0.1
Time Horizon			Q1Y1	Q1Y1→Q2Y2	...	...	Q1Y1→Q2Y2	Q3Y2→Q4Y2	Q1Y3→Q2Y3	Q3Y3→Q4Y3	

COMMENTS:

5. Rated Assessment Criteria (minimum ¼ page, maximum ½ page of text each)

Please describe your proposal in terms of:

5a. Phase 1 Selection:

1) Problem Definition (Weight = 0.25)

Problem This proposal investigates the feasibility of enforcing a collaborative and adaptive behaviour among undersea networked sensors through (i) nature's inspired adaptations, (ii) a data-aggregation technique taking into account infrequent communication, and (iii) a decentralization of the mission-critical computation and knowledge.

Scientific Merit In Section 2 "Purpose & Objectives", we state realistic assumptions, a strong research hypothesis, and clear objectives about a challenging network problem that is relevant for communication-opaque undersea environments. Nature's capability to collaborate despite infrequent communication and limited computation strongly inspires this proposal, and the collaborative behaviour exhibited by wolves hunting as a pack captures its essence. This proposal also capitalizes on timely technological progress such as improved in-sensor computational capabilities and mounting evidence about bio-inspired adaptation techniques that recently led to significant breakthroughs.

Literature Review In the "Background" part of Section 2, we demonstrate that this problem is fundamentally difficult and yet not fully resolved by any research group in the world. Partial solutions to sub-problems may be found in the literature, but no particular contribution addresses the problem as a whole in the context of an underwater environment. However, the fact that nature so perfectly enforces collaboration in restrained-communication conditions indicates that this proposal's objective is realistic and reachable.

2) Research Plan & Methodology (Weight = 0.25)

Plan & Methodology For this proposal to succeed, the project team needs to develop new techniques adapted to an undersea context. Section 2 "Approach & Methods" and Section 4 "Project Work Plan" provide the rationale and the logic of the plan which promotes progressive developmental steps (theory ⇒ simulations ⇒ experiments), the parallelization of technical goals (b)-(e), and the two-step experiments (lab ⇒ real systems). Specific methods for investigating the project technical goals are sufficiently detailed in Section 2 "Approach & Methods" for both theoretical and experimental aspects of this research. Section 4 "Project Work Plan" indicates two important milestones and decision points at Activity Phase 5 and Activity Phase 7 where the work plan may require significant adjustments and re-alignment with military-relevant features in case of failure.

Experiments As for the experiments, DRDC Valcartier and DRDC Atlantic will provide most of the required equipment, support and facility. For the undersea experimental portion of the project, we envision two potential sites: the Bedford Basin (Halifax, NS) and the Canadian Forces Maritime Experimental Test Ranges (near Parksville, BC). Depending on the sea experimental site, we may use DRDC Atlantic's barge, sensors, projectors, DND vessels, and U. of Victoria or DRDC UAV. DRDC Atlantic has tremendous experience conducting experiments at these locations.

Use of Funds Funds will be utilized for supporting external contracts with university faculties and other contractors helping setting up experiments. The use of DND and DRDC equipment and support personnel for the experiments alone amounts to about $300K. Overall, internal contributions represent 136% of the required $750K TIF investment, which is substantiated by a detailed work breakdown (see "Project Work Plan"). The level of funding requested reflects the necessity to fully engage universities' brain power for investigating the proof-of-concept feasibility in a timely and efficient manner. To maximize this fundamental research momentum, this proposal promotes frequent face-to-face meetings and encourages graduate students or post-doctoral researchers to visit and work at DRDC centers. We will reduce the impact of overhead activities by seeking additional funding from external team members.

3) Team (Weight = 0.25)

Composition A world-class team of experts with complementary skills has been assembled. External collaborators from universities were sought after because this proposal is at the leading edge of the theory on collaboration and adaptation over sensor-networks. As a whole, the team has many years of experience in technological implementation; thus, enabling thorough theoretical and experimentation plans and procedures. A brief biography of each team member is provided at the end of this document. The team size is adequate in the sense that its small size will facilitate project management, while at the same time being large enough to generate research momentum. This momentum will be strengthened by the collaboration resulting from the physical proximity of four of the six fully-engaged team members. The principal investigator has many years of industrial experience at developing and transitioning technology to clients.

Team Coordination In addition to monthly meetings, we intend to have the graduate students and post-doctoral researchers work at DRDC centers for short periods of time, security clearance permitting. The purpose here is to engage with most contributors early in the life of the project so that research activities remain well coordinated and in line with the research plan and objectives. In return, these close collaborations will benefit to DRDC personnel in the form of direct knowledge transfer.

Commitment Through this team collaboration, we gain access to the necessary experimental equipment, that is, DRDC Valcartier for indoor fixed and mobile sensors, DRDC Atlantic for undersea fixed and mobile sensors, and the McGill Computer Networks Research Lab for elaborate pre-experiment simulations. The project team is fully committed, highly motivated and competently trained to support all of the proposed activities. Recent exchanges among team members are filled with a rare level of excitement about the potential outcomes of this proposal.

4) Novelty (Weight = 0.25)

This proposal is at the leading edge of the theory and practice on collaboration and adaptation over sensor-networks. Indeed, there currently exists no computational scheme or algorithm enforcing such behaviours in an unsupervised and decentralized manner among undersea networked-sensors subject to intermittent communications. This proposal novelty hinges on three distinct features *collaboration, decentralization* and *adaptation* combined for the first time in a single undersea-sensor research effort. Through this proposal, collaboration will take place via network communications, data exchange, underwater vehicle mobility and data-aggregation. Unlike classic data-aggregation techniques, the proposed technique will model network connectivity and structure based on the theory of directed and dynamic graphs [59]. Decentralization of network knowledge and computation represents a novel and challenging departure from state-of-the-art research. This implies that network nodes must continually learn of the presence and status of other nodes as well as of the overall network connectivity. Adaptation is a must to guarantee satisfactory unsupervised behaviours. Adaptation is particularly well-suited for "learning on the fly" in the highly dynamic undersea environment influencing wireless communications.

To solve this very challenging problem, a novel combination of techniques will be needed from distinct research areas such as Self-organizing Systems [60], Evolutionary Computation [49], Extremum-Seeking [51], and Reinforcement Learning [52], just to name a few. The principal investigator has experience combining principles from some of these fields, whose synergy proved transformational in the industry [61, 62]. Taken separately, collaboration, decentralization or adaptation is novel for undersea networks; together, these features represent a revolutionary way of performing undersea surveillance.

5b. Phase 2 Selection:

1) Capability Development (Weight = 0.25)

Development of In-house Capabilities Interactions with world-caliber university professors will enable the transfer of up-to-date knowledge and tools about collaborative and adaptive undersea sensor-networks to both DRDC and DND personnel. Through the execution of this project, DND will gain the capability of deploying and operating such networks and potentially extend the technological concept to air, surface, and land operations. The same concepts could apply to security and law enforcement agencies for surveillance operations. In case an opposing force develops a similar undersea surveillance technology, this proposal will exploit the knowledge gained to design a set of appropriate counter measures that would render CF submarines stealthier.

Improve Defence & Security S&T Today's use of undersea sensing technology for surveillance purposes could be qualified as requiring high-bandwidth and frequent communication, a centralized data-aggregation, and significant operator and analyst overhead. This research proposition is meant to improve the wireless undersea surveillance capability by reducing the communication frequency, decentralizing data aggregation, and only requiring operator interventions for tough decisions. In this sense, this proposal will reduce operational risks by keeping assets and personnel at a greater standoff distance, while improving the sensor effectiveness by maximizing their collective performance in dynamically changing undersea environments.

Enable Defence & Security S&T To the best of our knowledge, military undersea-surveillance networks are wired; thus requiring an overt installation phase. Moreover, their operation necessitates a significant operator or analyst overhead. These characteristics limit such networks to friendly waters and to a humanly-manageable analysis capacity. By making wireless undersea sensors behave like an intelligent collective entity through collaboration and adaptation, we allow a manageable increase in their deployments, and enable covert deployments and operations in many regions.

2) Impact (Weight = 0.25)

Military Today's military sensors enable the collection of a massive amount of data, often analyzed offline. Tomorrow's militaries will dominate by making sense of that data in real-time. Such dominance could materialize by supporting this proposal which could (1) reduce submarine threat exposure, (2) increase standoff distance as the sensor-network will operate with limited supervision, (3) enhance protection and survivability of CF and national assets, (4) provide a new concept of undersea sensor employment maximizing sensors' coverage, (5) accelerate the first two stages of the observe-orient-decide-act (OODA) loop through collaboration and adaptation, (6) increase sensors' covertness by reduced communication, (7) enable unsupervised surveillance for choke points, confined areas and ice-covered areas, (8) provide an undersea surveillance capability that could be deployed and operated covertly, and (9) identify countermeasures to render CF submarines stealthier. **External Agencies** As indicated below in "Application of Knowledge Gained", results from this research could apply to numerous scenarios. Government agencies (Fisheries and Oceans Canada, Canadian Coast Guard, Royal Canadian Mounted Police, etc.) and industry could exploit this technology for enforcing unsupervised surveillance of specific Arctic regions, protected or delimited zones, etc. For such agencies, this research has a high impact because it offers them a novel automated technology extending their current capabilities. **Return on Investment** If supported, this proposal could make DRDC and Canada world-leaders on collaborative and adaptive undersea networks, thus possibly leading to additional funding from DARPA, ONR, and NATO. This project will also leverage existing projects and external funding from university collaborators. DRDC Atlantic's S&T portfolio would gain at supporting this proposition as its outcome will benefit many future projects involving sensors. By engaging with graduate students and post-doctoral researchers, this project prepares the future generation of DRDC Defence Scientists. Following this TIF, the path to exploitation would be an ARP focused on deep ocean operations, a TDP testing a covert deployment in deep ocean, and ultimately a technology transfer to the CF. The principal investigator experience at commercializing new technologies will ensure that TIF funding is well spent to guarantee the ensuing ARP, TDP, and transfer activities. **Application of Knowledge Gained** The project solutions could apply to similar limited-communication military and civilian problems with land, surface, and air sensors in degraded environments (*e.g.*, littoral interferences) and denied environments (*e.g.*, signal jamming). Broad and numerous applications could follow from this research because the resulting algorithms will be made portable to any fixed and mobile sensors. The knowledge gained from this project will improve DND/DRDC overall ability to deploy collaborative and adaptive networks, and will facilitate DRDC's proactive approach to anticipated CF needs.

3) Organizational Fit (Weight = 0.25)

This proposal aligns with and will benefit to two enduring and core DRDC Atlantic priorities, i.e., *Undersea Warfare* and *Arctic Surveillance and Operations* [F], by making step-change enhancements to the overall performance of wireless undersea sensor platforms.

At the corporate level, this research proposition will impact four of the eleven DRDC S&T Areas found in the Defence S&T Strategy (*01 Command and Control*, *02 Communications Networks*, *03 Intelligence Surveillance and Reconnaissance*, and *06 Mobile Systems*) [G], and will alleviate deficiencies in *People, Knowledge and Expertise* as well as in *Infrastructure and Tools* [H].

The proposed research is relevant to DND/DRDC S&T strategy as it naturally extends activities like RDS TDP (15AJ), DSP2 ARP (11CC), LCAN (11CL), Northern Watch TDP (11EJ), Active Sonar TDP (11CM), and the AMASE TDP (11CM). Indeed, the project outcome has the potential to greatly enhance undersea sensing platforms' performance by tailoring their communication and data aggregation to dynamic undersea environments. While avoiding duplication of efforts, this proposition will capitalize on the conclusions of some on-going projects across DRDC [I,J,K,L].

In its 2008-2030 vision, DND highlights that *Automation*, *Information, Computing Technology, Sensors,* and *Network Technologies* altogether "will underpin many of the technological breakthroughs that will contribute to future defence and security capabilities" [A, page 82]. Being at the forefront of all these fields, this research project is in line with DND's capability vision. Recent Navy requirements [C] indicate that the proposed research will directly support the *Maritime Information Battle Space* and the *Underwater Battle Space* objectives of the Research, Technology and Analysis (RTA) Programme by investigating constrained bandwidth (MI#1), self-forming networks (MI#3), persistent surveillance (MI#5), submerged data exchange (UW#1), new ASW technology (UW#4), and management of sensor information (UW#5). Another recent document from the Canadian Forces Maritime Warfare Center (CFMWC) explicitly stresses the necessity of robust data aggregation techniques for multi-sensor operations [B, page 6].

In addition to its strong alignment with DND/DRDC S&T priorities, the proposed research demonstrates a fit with key naval objectives of one of our most important military and NATO allies. Indeed, in the strategic review of the Office of Naval Research (ONR) [64, page 14], the "Assure Access to the Maritime Battlespace" capability sets key objectives exploiting the fields of *Adaptation, Automation, Off-board Sensing, Collaboration, Networking,* and *Next-generation Data Aggregation* in the submarine warfare theater.

4) Risk Potential (Weight = 0.25)

This proposal represents leading-edge theoretical and practical research. Indeed, no other research group has ever implemented or operated such collaborative and adaptive undersea sensor-network. As reported in the "Background" part of Section 2, the literature in mainstream science has not yet addressed many important aspects related to such networks.Theoretical and practical limitations are yet unknown as theory may lead to unfeasible conditions, and even if theoretical results prove feasibility, it does not preclude severe computational challenges. Moreover, this research proposition requires a non-conventional combination of existing technologies and new theoretical results adapted to undersea communication. The project technical goals defined in Section 2 are such that the failure of any of them could lead to a drastic reduction of network performance and military impact. Based on the above attributes, we believe this project qualifies as high-risk.

The "Risk Mitigation" part of Section 2 and Section 4 "Project Work Plan" provide mitigation strategies for scientific risks. These risks include a theoretically or practically proven weak collaboration capability in the presence of network knowledge decentralization and an infeasible implementation. The proposal addresses how the scientific risk will be mitigated by incorporating parallel research paths allowing independent development and testing toward the end goal of a collaborative and adaptive undersea network. The proposed experimental route promotes an approach in which the experimental platforms is progressively made more realistic by starting with a simulated environment, followed by a dry-lab experiment with real sensors, to culminate with an "at sea" controlled experiment. The project plan was carefully designed to ensure that parallel research paths and sequential experiments would yield valuable data and knowledge by standing independently on their own. The failure of some key activities may cause delays but even in the eventuality of a timeline slippage, the TIF funding will still help pass key scientific hurdles because the most difficult tasks are looked after first in the Section 4 "Project Work Plan".

To give another perspective on the present risk level, the Defense Advanced Research Projects Agency (DARPA), which is known for sponsoring only high-risk and high-payoff projects, has recently funded similar bio-inspired projects such as "Biologically-driven Navigation" (solicitation number DARPA-SN-11-07), "Deep Sea Operations" (DARPA-BAA-11-24), and "All Source Positioning and Navigation" (DARPA-BAA-11-14), just to name a few.

6. External Reviewer Suggestions **(Please ensure conflict of interest is avoided, and that proposed reviewer is available and agrees to participate)**

Salutation/First/Last/Affiliation	Area of Expertise	Address / Phone / E-mail
Dr./ Ali/ Jadbabaie / University of Pennsylvania, Electrical & Systems Engineering	Network, Consensus, Control, Optimization	200 South 33rd Street Philadelphia, PA 19104, USA /(215) 898-8105 /jadbabai@seas.upenn.edu
Dr./ Reza/ Olfati-Saber / Dartmouth College, Thayer School of Engineering	Consensus, Control, Machine Learning	8000 Cummings Hall Hanover, NH 03755, USA /603-646-0204 /olfati@dartmouth.edu
Dr./ Mehran / Mesbahi / University of Washington, Aeronautics & Astronautics	Control, Unmanned Vehicles, Optimization	211 Guggenheim Hall Seattle, WA 98195-2400, USA /(206) 543-7937 / mesbahi@aa.washington.edu
Dr./ Ali H. / Sayed / University of California Electrical Engineering Dept.	Adaptation, Learning, Bio-inspired networks	56-125B Engineering IV Building Los Angeles, CA 90095, USA. /(310) 267-2142 /sayed@ee.ucla.edu
Dr./ Antonios/ Tsourdos/ Cranfield University (Defence College of Management and Technology)	Cooperative control, Weapons Guidance, Navigation, Mission & path planning	Shrivenham Swindon SN6 8LA U.K. /+44 (0)1793 785841 /A.Tsourdos@cranfield.ac.uk

COMMENTS:

7. Financial Summary

Planning Year	Year 1	Year 2	Year 3	Total
7a. FUNDING REQUESTED FROM TIF PROGRAM $K:				
R&D Contracts	363	283	60	705
Project O&M	20	15	10	45
TOTAL TIF $K	**383**	**298**	**70**	**750**
7b. INTERNAL CONTRIBUTIONS				
SWE (*2.4)	312	192	168	672
O&M (non-travel)	15	15	25	55
R&D Equipment				
(DRDC V – PW)	0	0	50	50
(DRDC A – MHD)	0	0	250	250
Travel	10	10	20	40
TOTAL LAB CONRIBUTION $K	**337**	**217**	**463**	**1017**
RATIO: INTERNAL CONTRIBUTION TO TIF FUNDING (divide part B total into part A total, express as %) [MINIMUM 70%]				**136%**
COMMENTS:				

2012
TECHNOLOGY INVESTMENT FUND (TIF) PROJECT PROPOSAL

SIGN OFF SHEET

Project Title: Adaptive Multi-sensor Biomimetics for Unsupervised Submarine Hunt (AMBUSH)
Principal Investigator: Stéphane Blouin

Comments:

The proposal addresses one of the most important problems in undersea warfare which is persistent situational awareness in the communication-limited undersea environment. Leveraging recent research in animal group behaviour in both communication- and computation-limited regimes is a very promising approach to realizing the potential of new undersea sensors and autonomous platforms. I fully support this proposal and will commit the internal resources required for it.

Section Head Signature: ________________________________ Date: __________________

Comments:

This well researched proposal is aimed at building science capability in a priority area for DRDC and has the potential to lead to a world beating approach to enabling effective undersea surveillance which could be exploited in priority Canadian Applications such as arctic surveillance.

This proposal fits within and will contribute to the S&T area responsibilities of the Centre. I concur with the suggested Peer Reviewers. I confirm that the resources being requested (both human and monetary) are consistent with requirements to execute the proposed research. I also confirm having consulted the Chief Scientists of each of the centres involved. This proposal fits within the mandate of the TIF.

Chief Scientist Signature: ________________________________ Date: _______________

Comments:

I approve commitment of the internal resources, facilities and laboratories required for the duration of this project.

DG Signature: ____________________________________ Date:___________________

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[I] TIF 12pz18 - *Self-Healing Networked Control Systems for Enhance Reliability and Safety of Multivehicle Missions* (ends FY 11/12). We may be using the multi-vehicle drone test-bed for experimentation purposes.

[J] ARP 13OC - *Artificial Intelligence for Computer-generated Forces* (ends FY 11/12). Simulation technology could be exploited by the proposed TIF.

[K] ARP 11CF – *Mine and Harbour Defence* (ends FY 12/13). In addition to anti-submarine warfare this maritime scenario would be a plausible one to investigate from a networked collaboration standpoint.

[L] TDP 11CM – *Advancing Multistatic Active Sonar Employment* (ends FY 14/15). This maritime scenario could also benefit from networked collaboration perspective.

BIOGRAPHIES

The team assembled to work on this project is comprised of experts in a variety of different, yet complimentary S&T areas that cover the full range of technical expertise for guaranteeing the success of this project.

Dr. Stéphane Blouin, DS-4, is a Defence Scientist and member of the System Architectures Group in the Technology Demonstration Section at Defence Research and Development Canada - Atlantic. Through publications and inventions he contributed to the field of Network Consensus, Automation, Real-time Monitoring, and Optimization via techniques pertaining to Extremum-seeking, Graph Theory, and Hybrid Systems. He has over 12 years of industrial R&D experience in developing and implementing novel automation technologies in various industries in Canada and abroad. Dr.Blouin is an Adjunct Professor at Dalhousie University.

Dr. Garry J. Heard, DS-6, is a Defence Scientist and the leader of the Network Autonomous Littoral Surveillance (NetALS) Group at Defence Research and Development Canada – Atlantic. The NetALS Group conducts research in underwater sensing and communications. A focus of the group has been to build and test off-board sensing systems employing acoustic, electromagnetic, and pressure sensors. The development of low-cost, low-power arrays with high-performance creates opportunities for persistent surveillance; the Northern Watch TDP is one such application. Dr. Heard has worked in Ocean and Arctic acoustics for the past 27 years.

Dr. Camille-Alain Rabbath, DS-4, is a Defence Scientist at Defence Research and Development Canada – Valcartier. He also holds adjunct professorship positions at Concordia University and Laval University. Dr. Rabbath received the PhD degree in 1999 from McGill University. He then worked in industry from 1999 to 2002 in control systems design, and in modeling and simulation of aerospace and robotic systems. Dr. Rabbath is currently Associate Editor for the journals IEEE Transactions on Control Systems Technology, Transactions of the Canadian Society for Mechanical Engineering, and Control Engineering Practice, and for the IEEE Canadian Review magazine. He is active in the development of cooperative unmanned systems with health monitoring, and decision-making capabilities. He has written several peer-reviewed publications in this area, including the 2010 book entitled "Safety and Reliability in Cooperating Unmanned Aerial Systems," published by World Scientific. Dr. Rabbath is a Senior Member of the IEEE.

Dr. Amir G. Aghdam is an Associate Professor in the Department of Electrical and Computer Engineering of Concordia University (Montreal, QC). His research interests include Decentralized Control of Large-scale Systems, Multi-agent Systems, Adaptive Switching Control, and Sampled-data Systems. Dr. Aghdam is an Associate Editor of the IEEE Systems Journal, and has been a Technical Program Committee Member of several IEEE conferences (ACC, CDC, etc.). He is a recipient of the 2009 IEEE MGA Achievement Award, and 2011 IEEE Canada J.J. Archambault Eastern Canada Merit Award. Dr. Aghdam's recent contributions include publications on Network Consensus using Graph and Control theoretical principles.

Dr. Michael Rabbat earned the B.Sc. from the University of Illinois at Urbana-Champaign (2001), the M.Sc. degree from Rice University (2003), and the Ph.D. from the University of Wisconsin-Madison (2006), all in electrical engineering. He is currently an Assistant Professor at McGill University. He received the Best Paper Award at the 2010 IEEE Conference on Distributed Computing in Sensor Systems (DCOSS), Outstanding Student Paper Honorable Mention at the 2006 Conference on Neural Information Processing Systems (NIPS), and the Best Student Paper Award at the 2004 ACM/IEEE Conference on Information Processing in Sensor Networks (IPSN). He currently serves as an Associate Editor for the ACM Transactions on Sensor Networks and for IEEE Signal Processing Letters, and he was Technical Program Chair for the 2012 IEEE International Conference on Distributed Computing in Sensor Systems. His research interests include signal processing, networks, and machine learning, with applications in communications, sensor networks, and information fusion.

Dr. Evangelos Kranakis received his B.Sc. in Mathematics from the University of Athens, Greece, and a Ph.D. in Mathematics from the University of Minnesota, USA. He has been in the Mathematics Department of Purdue University, USA, Mathematisches Institut of the University of Heidelberg, Germany, the Computer Science Department of Yale University, USA, at the Computer Science Department of the Universiteit van Amsterdam, and at the Centrum voor Wiskunde en Informatica (CWI) in Amsterdam, The Netherlands. He joined the faculty of the School of Computer Science of Carleton University in the Fall of 1991. He has published in the analysis of algorithms, bioinformatics, communication and data (ad hoc and wireless) networks, computational and combinatorial geometry, distributed computing, and network security. He was director of the School of Computer Science from 1994 to 2000 and is currently Chancellor's Professor at Carleton University.

ACRONYMS

ARP	*Applied Research Program*
ASW	*Anti-Submarine Warfare*
AUV	*Autonomous Underwater Vehicle*
CF	*Canadian Forces*
CFMWC	*Canadian Forces Maritime Warfare Center*
CRC	*Communications Research Centre*
DARPA	*Defense Advanced Research Projects Agency*
DND	*Department of National Defence*
DRDC	*Defence Research and Development Canada*
LCdr	*Lieutenant-Commander*
NATO	*North Atlantic Treaty Organization*
NURC	*NATO Undersea Research Center*
ONR	*Office of Naval Research*
OODA	*Observe, Orient, Decide, Act*
PY	*Person-year*
QxYz	*Quarter "x" of Year "z"*
RTA	*Research, Technology and Analysis*
S&T	*Science and Technology*
TDP	*Technology Demonstration Program*
TIF	*Technology Investment Fund*
TM	*Technical Memorandum*

Annex C: Letter of appreciation

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17 March 2015

Dan Hutt
Defence Research and Development Canada,
Dartmouth, NS

RE: USE OF TEST TANK FOR EXPLORATORY MEASUREMENTS RELATED TO SMALL, LOW POWER AND AUTONOMOUS ARRAY SIGNAL PROCESSORS

I am writing this letter to express my gratitude for the use of the freshwater test tank at your facilities on March 12, 2015. My company, Turbulent Research, in collaboration with Dalhousie University, have built a broadband multi-element passive acoustic recorder and real time signal processor for underwater monitoring. We are exploring the use of novel, real time, low power array signal processing techniques to mitigate hydrodynamic flow noise and enhance passive acoustic detection and underwater communication range with compact hydrophone arrays. This work is to be presented at the OCEANS15 conference in Genova, Italy in May.

To prove our hypothesis related to signal enhancement and improved signal to noise ratio, it was imperative that we get real world data. To test this device in the ocean would have been prohibitive in terms of both deployment costs and time, especially for a small company like Turbulent Research. The use of the DRDC test facility has allowed us to collect high quality data, quickly, under a number of unique test scenarios. This work would not have been possible without the use of the DRDC test tank.

We worked with some excellent technologists and scientists who made things run smoothly, this required very serious effort in terms of setup, processing and instrument control. Specifically, Ricky Vienneau, Dang Phan, Mark Fotheringham, Jeff Scrutton, and Stephane Blouin were instrumental in helping successfully complete this testing. It is my hope that access to this data and knowledge of our unique and cutting edge underwater instrument and signal processing methods can provide significant value back to DRDC in the future.

Best regards,

Chris Loadman,

President, Turbulent Research Incorporated

Annex D: Main publications

D.1 Journal papers

[Q113] "Is your world complex? An overview of complexity science and its potential for military application"

Assumptions

- None.

Main conclusions

- Complexity concepts, tools, and principles are applicable to understanding and enhancing military effectiveness.
- Numerous examples showed that complexity concepts can impact military decisions at the tactical, strategic, and operational levels.
- Recent research trends include influencing the emergent behaviour of man-made complex systems.
- Results using complexity concepts often lead to unconventional guidance emphasizing autonomy, decentralization and adaptation, and diminishing the importance of long-term predictions and rigid hierarchies.
- Complexity remains a promising framework to study questions pertaining to military structures and operations, due to their strong similarities with how living organisms survive through adaptation, competition, and cooperation.

Potential extensions

- None.

[B6] "Error propagation in gossip-based distributed particle filters"

Assumptions

- Multiple sensors track a known number of targets.
- Each sensor gathers local measurements, updates a local particle filter, and sensors communicate to fuse/synchronize their particle filters.
- Nodes remain exactly synchronized after each round of communication. This is equivalent to running a fixed number of approximate distributed averaging iterations, followed by max consensus iterations to achieve exact synchronization (i.e., zero disagreement), although we do not require that all nodes exactly compute the average.

Main conclusions

- As long as the error introduced by approximate distributed averaging remains bounded, the distributed particle filters remain stable: the difference between the particle distribution and the density of the ideal (but unimplementable) Bayes optimal recursion remains bounded over all time.

– An upper bound on the worst-case steady-state error is determined as a function of: a) the number of particles, b) the error between distributed log-likelihood calculation (e.g., via gossip), and the joint log-likelihood one would compute of all measurements were available at a centralized location, and c) parameters related to the target dynamics and measurement model.

– The worst-case steady-state error is proportional to $1/\sqrt{N}$, where N is the number of particles, so increasing the number of particles reduces the error accordingly.

– The worst-case steady-state error decreases linearly with respect to the error δ introduced by gossip.

– An expression is provided for the simple case of gossiping on each individual particle weight to relate the number of gossip iterations ℓ to the error δ. In general, the gossip error δ decays like $\delta \approx C^{\ell}$, where C is a positive constant less than 1 which depends on the network size and topology. Thus, increasing the number of gossip iterations decreases the gossip error and hence decreases the worst-case steady-state tracking error.

Potential extensions

– Derive similar stability and error bounds for the case where sensors do not necessarily achieve zero disagreement, but rather maintain a bounded disagreement after each round of communication.

– Analyze particular particle filter compression schemes (e.g., the graph-Laplacian or clustering-based schemes from conference papers 4 and 5) to quantify the approximation error they introduce and obtain performance guarantees for these methods.

– Study the effect of the absence of synchronization.

[B7] "Multi-sensor CPHD filter"

Assumptions

– Multiple sensors transmit measurements to a central location for processing.

– The number of targets may vary over time.

– Sensors gather both legitimate, target-generated measurements and clutter.

– There is at most one measurement at each sensor corresponding to each target per time step.

– There is a known non-zero probability that a sensor may not detect a target in its field-of-view.

Main conclusions

– The exact update equations for the (centralized) *cardinalized probability hypothesis density* (CPHD) filter are derived.

– The exact update is intractable to implement in general (requires enumerating all subsets of the measurements), so an approximate implementation is proposed.
– The proposed implementation offers superior tracking performance compared to other heuristic multi-sensor CPHD approaches described in the literature.
– In particular, other approaches process sensor measurements sequentially and exhibit a strong dependence on the order in which the sensors are processed.
– The performance of the proposed approach is not order-dependent.
– The computational complexity of the proposed approximate implementation is linearly proportional to the number of sensors.

Potential extensions

– Develop a principled multi-sensor version of the Multi-Bernoulli filter.
– Develop distributed (consensus/gossip-based) versions of the CPHD or other random finite set filters (e.g., multi-Bernoulli).

[B8] "A distributed particle filter for bearings-only tracking on spherical surfaces"

Assumptions

– Multiple sensors track a single target.
– The world is a sphere (use spherical coordinates).
– Sensors gather noisy bearing measurements.
– Measurement noise is additive and Gaussian with known variance.
– Nodes run local particle filters and perform fusion by averaging six sufficient statistics.
– The communication topology is static, symmetric, and nodes perform synchronous updates.

Main conclusions

– The performance of the proposed approach is compared with that of a similar distributed particle filter that uses a planar approximation to the sphere, tangent to the estimated target position.
– Both methods have the same communication overhead, which is considerably lower than that of more general-purpose distributed particle filters (i.e., not specifically for a single target with bearings-only measurements and additive Gaussian noise).
– The two approaches (planar approximation, and proposed based on spherical coordinates) offer comparable performance when the target is near the equator, regardless of the distance from the target to the sensors.

- When the target is not near the equator, accuracy of the planar approximation decays, especially as the distance from sensors to target increases; this decay is amplified as the target gets closer to the poles.
- The proposed approach using spherical coordinates offers performance comparable to that of a centralized particle filter with access to all of the measurements regardless of the distance from sensors to target or the latitude of the target.

Potential extensions

- None.

[B9] "Distributed consensus control of unicycle agents in the presence of external disturbances"

Assumptions

- Upper bounds on the magnitudes of the disturbances are assumed to be available.
- The information flow graph of the network is assumed to be connected and static.

Main conclusions

- A distributed consensus control strategy is presented in this work for a team of unicycle agents subject to external disturbances.
- Bounded disturbances with unknown dynamics on both translational and angular velocities are applied to the system.
- The main idea is to design the control inputs of each agent in such a way that, after a finite time, agents move with an acute angle with respect to a reference vector typically used for the consensus control of disturbance-free single-integrator agents.
- Convergence to consensus is then proved using Lyapunov theory.

Potential extensions

- The distributed consensus control in presence of disturbances can be investigated for networks with switching topologies and communication time-delays.

[B10] "Connectivity assessment of random directed graphs with applications to underwater sensor networks"

Assumptions

- The expected communication graph of the network is assumed to be strongly connected.

Main conclusions

- The problem of connectivity assessment for a random network is investigated.

- The weighted vertex connectivity (WVC) is defined as a metric to evaluate the connectivity of the weighted expected graph of a random sensor network where the elements of the weight matrix characterize the operational probability of their corresponding communication links.
- The WVC measure extends the notion of vertex connectivity for random graphs by taking into account the joint effects of the path reliability and the network robustness to node failure.
- The problem of finding the WVC measure is transformed into a sequence of iterative deepening depth-first search and maximum weight clique problems, and based on that, an algorithm is developed to find the proposed connectivity metric.

Potential extensions

- Provide an approximation of the proposed WVC measure which can be computed by a time-efficient algorithm.

[B11] "Expected convergence rate to consensus over asymmetric networks: Analysis and distributed estimation"

Assumptions

- The network is quasi-strongly connected.

Main conclusions

- The new concept of *expected convergence rate* (or ECR) is defined as the convergence rate of a consensus-like algorithm on average over a set of randomly-chosen initial network node state.
- An extension of the power-iteration algorithm is derived to provide the minimum eigenvalues and eigenvectors of a matrix.
- A variant of the Krylov subspace method is proposed to generate an approximation of the ECR.
- A distributed computation of ECR is performed using a consensus observer.

Potential extensions

- Given the large number of tuning parameters resulting from the nested proposed techniques, a paper clarifying the bounds and an optimization approach would be helpful for potential users of this technology.

[B12] "Simulation and modelling of hydro acoustic communication channels with wide band attenuation and ambient noise"

Assumptions

- Attenuation (frequency and distance dependent) based on Thorp model.
- Ambient coloured noise.
- Multipath propagation (reflection and refraction).

Main conclusions

– Multiple models, coherent and incoherent, were proposed to capture frequency-dependent acoustic noise.
– Models with coherent attenuation result in worse performance, in terms of Bit Error Rates (BERs), compared to the models with incoherent attenuation.
– The proposed incoherent linear fitting model has simulation results slightly worse than the ones of a baseline model [Proakis and Salehi 2007].
– The BERs of two proposed incoherent models are very close, but the linear fitting model needs much less running time.
– The BERs of the proposed coherent model are obviously worse than the baseline model.
– The coherent attenuation is such that the BERs of coherent models cannot drop down to zero, even if the noise is nil.
– Colored noise impacts the system performance more than white noise for all models, due to the frequency-dependent nature of coloured noise. For the incoherent models, when the E_b/N_0 ratio rises, the BERs with AWGN (Additive White Gaussian Noise) decrease more steeply than with coloured noise. However, for the coherent models with coloured noise, the BER is falling almost the same as for the coherent models with white noise.
– The attenuation of the coherent models is larger than for all the incoherent models. The noise has less effects on the BERs in the coherent models than in the incoherent models.
– The BER curve of the coherent multi-frequency-pressure-sum model with coloured noise is most similar to the BER curve of the field experimental data.

Potential extensions

– None.

D.2 Conference papers

[C13] "Intermission-based adaptive structure estimation of wireless underwater networks"

Assumptions

– Only one node acoustically broadcasts its network information and reception of the broadcast by other nodes is probabilistic in nature.
– Each node starts without any knowledge about the network.
– Probability of reception of a communication may vary over time.
– Network nodes could be added or removed dynamically.
– The network structure estimation technique (size and composition) assumes a decentralized approach.

Main conclusions

- There is a clear communication benefit of transmitting each node network structure estimate. The effect gets stronger the lower the probability of reception becomes.
- Intermissions (deadtime between communications) can be used to set up a learning mechanism for estimating a network structure.
- The resulting algorithm is simple and only require two user inputs.

Potential extensions

- Break the single time-division broadcast to multiple local time-division broadcasts and show how speed and/or throughput can improve.

[C15] "Toward distributed noise-source localization for underwater sensor network"

Assumptions

- This paper develops a technique to help an acoustic sensor select the most relevant bearing pertaining to a target thus reducing the node-to-node communication overhead.
- Single target is present.
- Each sensor can generate a signal-to-noise ratio (SNR), bearing, and time-of-arrival for each acoustic detection.
- A simplified second-order model captures the SNR-to-arrival relationship, which help identify the existence of a direct path.
- A Finite-State Machine approach is used to perform anomaly detections among multiple bearing estimates.

Main conclusions

- Compared to a traditional SNR-threshold bearing selection, the proposed approach results in a tighter bearing standard deviation with fewer anomalies.
- The acoustic data suggests that some channel characteristics may not relate to sensor proximity.

Potential extensions

- Prove that expected arrivals match the pattern described by a second-order impulse response.
- Re-analyze the data along with direct path calculation using the refracted communication paper result.
- Assume a more robust Finite State Machine to avoid the behaviour reported in the publication.

[C16] "Adaptive multi-sensor biomimetics for unsupervised submarine hunt (AMBUSH): Early results"

Assumptions

- This paper summarizes the first year of the AMBUSH and as such contains the same assumptions.

Main conclusions

- The entire set of twenty-six distinct findings can be found in the paper.

Potential extensions

- None.

[C17] "Localization error of underwater multistatic scenarios with uncertain transducers' location"

Assumptions

- Position errors for the source and all receivers are assumed.
- Position errors take the form of a circular region centered at the transducer location.
- Single target evolves in a two-dimensional space.
- Depth-independent and constant sound speed (iso-velocity).
- Only time-of-arrivals are used, no bearing estimate information is used.

Main conclusions

- Proposed a multistatic active localization error estimate and upper bound for situations with inaccurately located source and receivers.
- The proposed localization error estimate can be exact and is better-conditioned than existing localization error estimates.
- The localization error upper bound does not require a bearing thus applying to simple hydrophones.

Potential extensions

- Extend the approach to acoustic paths whose sound speed is different and develop approach for a network made of sensors with a single hydrophone.
- Validate concept using real underwater acoustic data.

[C18] "Refracted acoustic communications in wireless underwater sensor networks with mobility"

Assumptions

- Using only refracted acoustic paths to do underwater node-to-node communication.
- The beamwidth and directionality of the acoustic energy are controllable.

– Sound speed profiles are of first-order (single slope) only.

Main conclusions

– Optimal network routing is performed based on the channel physics and transmission losses.

– Necessary and sufficient conditions guaranteeing the existence of a single-hop link through an acoustic refracted path are derived.

Potential extensions

– Extend the first-order sound speed profile to a more complicated and realistic sound speed profile.

– Add some non-blocking features.

– Consider the Arctic sound speed profiles and vertical routing.

[C19] "Autonomy and networking challenges of future underwater systems"

Assumptions

– None.

Main conclusions

– A list of 6 autonomy and networking challenges is derived.

Potential extensions

– None.

[C20] "Distributed underwater acoustic source localization and tracking"

Assumptions

– Multiple sensors track a single target.

– Sensors gather bearing and time-of-arrival measurements.

– Nodes run local particle filters and fuse using consensus directly on particle weights.

– The communication topology is static, symmetric, and nodes perform synchronous updates.

Main conclusions

– Experimental results obtained on DRDC's Q347 dataset.

– Particle filtering approaches provide much higher accuracy on this dataset compared to an approach based on approximating the particle cloud with a single Gaussian density.

– Particle filtering approaches also have a much higher communication overhead.

Potential extensions

- Develop gossip-based distributed particle filters with asynchronous communication over possibly-directed, possibly time-varying network topologies.

[C21] "General solution and approximate implementation of the multisensor multitarget CPHD filter"

Assumptions

- Multiple sensors transmit measurements to a central location for processing.
- The number of targets may be time-varying.
- Sensors gather some legitimate measurements as well as clutter.
- There is at most one measurement at each sensor corresponding to each target per time step.
- There is a known non-zero probability that a sensor may not detect a target in its field-of-view.

Main conclusions

- The exact update equations for the *cardinalized probability hypothesis density* (CPHD) filter are derived.
- Those equations are intractable to implement, so an approximate implementation is proposed.
- The proposed implementation offers superior tracking performance compared to other heuristic multi-sensor CPHD approaches described in the literature.
- In particular, other approaches process sensor measurements sequentially and exhibit a strong dependence on the order in which the sensors are processed.
- The performance of the proposed approach is not order-dependent.

Potential extensions

- See related journal paper [B7].

[C22] "Performance investigation on constraint sufficient statistics distributed particle filter"

Assumptions

- Multiple sensors track a single target.
- The world is a sphere (use spherical coordinates).
- Sensors gather noisy bearings measurements.
- Measurement noise is additive and Gaussian with known variance.
- Nodes run local particle filters and perform fusion by averaging six sufficient statistics.
- The communication topology is static, symmetric, and nodes perform synchronous updates.
- Two fusion schemes are studied: exact and approximate.

Main conclusions

- The exact scheme has a communication overhead that is proportional to the number of particles, and its performance is sensitive to the placement of sensors.
- In particular, if sensors are not uniformly placed around the target then the resulting estimates are biased.
- The approximate scheme has a communication overhead that is independent of the number of particles used and its performance is not sensitive to sensor placement.
- The approximate scheme is less accurate than the exact scheme when the noise variance is small and the sensors are uniformly spaced around the target.
- Otherwise, the approximate scheme provides equal or better accuracy.

Potential extensions

- See related journal paper [B8].

[C23] "Particle weight approximation with clustering for gossip-based distributed particle fitlers"

Assumptions

- Multiple sensors cooperate to track a known number of targets in a decentralized manner.
- Each sensor runs a local particle filter and the network uses gossip to keep the filters at each node synchronized.
- To reduce communication overhead, sensors first group particles into clusters and aggregate particle weights within each cluster.
- Then they gossip on the aggregated cluster weights, rather than on the weights of individual particles.
- After gossiping, to recover individual particle weights from the averaged cluster weight values, each node solves an equality-constrained quadratic program.

Main conclusions

- In experiments with synthetic data and data from the Q347 at-sea trial, the proposed approach provides a promising tradeoff between communication overhead and tracking accuracy.
- There is an added cost of additional computation at each node to solve the quadratic program.
- The amount of communication overhead is proportional to the number of clusters; fewer clusters leads to lower communication overhead, but also lower accuracy.

Potential extensions

- The results in this paper are only based on numerical experiments. Develop theory to support the results. In particular, provide theoretical bounds on worst-case tracking accuracy as a function of the number of clusters used.
- Explore alternative approaches to the quadratic program for interpolating cluster-averaged values back to per-particle weights.

[C24] "Graph Laplacian distributed particle filtering"

Assumptions

- Multiple sensors cooperate to track a known number of targets in a decentralized manner.
- Each sensor runs a local particle filter and the network uses gossip to keep the filters at each node synchronized.
- To reduce communication overhead, sensors first fit a graph to their local particle cloud.
- Then, sensors compress their local particle weights by projecting them onto the subspace spanned by the first k eigenvectors of the graph Laplacian matrix.
- When k equals the number of particles then the representation is exact and there are no savings in communication overhead; when k is smaller than the number of particles the representation is approximate and the communication overhead is reduced.
- Sensors gossip on these Laplacian coefficients instead of on weights directly.
- Sensors update synchronously, in the sense that there are synchronous phases of gathering measurements and then fusing using gossip; asynchronous gossip algorithms may be used during the fusion stages.
- We assume that after each fusion round, all sensors are precisely synchronized (e.g., after a fixed number of distributed averaging iterations, nodes run a max consensus algorithm to agree exactly on the maximum value after a finite number of iterations).

Main conclusions

- Experimental results with simulated data suggest the proposed approach offers a promising tradeoff between communication overhead and tracking accuracy.
- Although the proposed approach has a higher communication overhead than approaches based on Gaussian approximation, it provides much higher tracking accuracy when target dynamics are non-linear or are driven by non-Gaussian process noise.
- The proposed approach has a much lower communication overhead than most other distributed particle filtering approaches in the literature (set-membership constrained, top-m selective gossip, and the accuracy is only moderately worse.

Potential extensions

– The results in this paper are only based on numerical experiments. Develop theory to support the results. In particular, provide theoretical bounds on worst-case tracking accuracy as a function of the number of graph Laplacian coefficients used and properties of the likelihood model (smoothness, etc.).

[C25] "Global network connectivity assessment via local data exchange for underwater acoustic sensor networks"

Assumptions

– The expected communication graph of the network is assumed to be strongly connected.

– It is assumed that only one successful broadcast can occur at a time in order to avoid transmission collisions and data interference.

Main conclusions

– The problem of distributed connectivity assessment for a network of underwater sensors in a data aggregation mission is studied in this paper.

– Motivated by a sufficient condition for asymptotic almost sure consensus in a network defined over a random digraph, vertex connectivity of the expected communication graph is used as a measure for connectivity of the underwater sensor network.

– A distributed update scheme is proposed in which the sensors update their perception of the expected communication graph.

– Since the expected communication graph is characterized by its associated probability matrix, a learning algorithm is employed by each sensor to update its belief on the probabilities using the messages it receives.

– Each sensor uses a polynomial-time algorithm to estimate the degree of vertex connectivity of the expected graph based on its perception of the network graph.

– The proposed algorithms can also handle changes in the topology of the network such as node addition, node deletion, and time-varying probabilities.

Potential extensions

– Instead of broadcasting the entire probability matrix estimated by each sensor to its neighbors, the measure of connectivity can be modified such that the communication complexity of the algorithm is reduced.

[C26] "A consensus control strategy for unicycles in the presence of disturbances"

Assumptions

– Disturbance dynamics is assumed to be linear and known with unknown initial conditions.

- The information flow graph of the network is assumed to be connected and static.

Main conclusions

- A distributed consensus control strategy for a team of unicycle agents subject to disturbances on both translational and angular velocities is presented.
- It is assumed that disturbance dynamics are known a priori while their initial conditions are unknown.
- The norm and the angle of a typical control vector for the consensus of disturbance-free single-integrator agents are used to design the proposed controllers.
- The control input for each agent consists of two parts, where the first part leads to consensus in disturbance-free case, and the second part compensates for the disturbances.

Potential extensions

- The proposed approach can be extended to the case of disturbances with unknown dynamics and networks with switching topologies.

[C27] "Joint power optimization and connectivity control problem over underwater random sensor networks"

Assumptions

- The expected communication graph is assumed to have a directed cycle topology.

Main conclusions

- Power optimization and connectivity control problems for an underwater random sensor network is investigated in this publication.
- The weighted edge connectivity is proposed as a metric to evaluate the connectivity of the weighted expected graph of a random sensor network where the elements of the weight matrix represent the operational probability of their corresponding communication links.
- The introduced connectivity measure is described as an explicit function of the transmission power of the sensors and the statistical parameters of the communication channels.
- An optimization problem is then presented to minimize the total power consumption of the network while a lower bound on the global weighted edge connectivity of the network is satisfied.
- An analytical solution to the optimization problem is obtained by considering a directed cycle topology for the expected communication graph.
- The efficacy of the obtained results is confirmed for log-normal distribution of the power gain of acoustic communication channels.

Potential extensions

– The connectivity control solution can be extended to more general topologies of the expected communication graph.

[C14] "Connectivity measures for random directed graphs with applications to underwater sensor networks"

Assumptions

– The expected communication graph of the network is assumed to be strongly connected.

Main conclusions

– The connectivity assessment problem for an underwater random sensor network is investigated in this paper.

– The weighted vertex connectivity (WVC) is introduced as a metric to evaluate the connectivity of the weighted expected graph of a random sensor network.

– Since the problem of computing the WVC measure is NP-hard, the approximate weighted vertex connectivity (AWVC) measure is defined subsequently as a lower bound on the introduced connectivity metric which can be computed by applying a polynomial-time shortest path algorithm.

– The performance of the proposed algorithms is validated using an experimental underwater acoustic sensor network.

Potential extensions

– Modify the proposed measure such that it can be computed in a distributed manner without requiring a global knowledge of the network topology.

[C28] "A computationally efficient connectivity measure for random graphs"

Assumptions

– The expected communication graph of the network is assumed to be strongly connected.

Main conclusions

– This paper investigates the global-connectivity assessment of a sensor network subject to random communications.

– Computing the weighted vertex connectivity (WVC) of the corresponding expected communication graph for such networks is an NP-hard problem.

– This situation led to the development of an approximate WVC (AWVC) measure, which has its own shortcomings.

– This paper introduces an improved approximate weighted vertex connectivity (IAWVC) measure with a polynomial-time algorithm.

– The new connectivity measure does not have the shortcomings of the AWVC measure and, under some conditions, matches the WVC measure.

Potential Extensions:

– None.

[C29] "Generalized algebraic connectivity for asymmetric networks"

Assumptions

– The underlying digraph of the network is quasi-strongly connected.

Main conclusions

– The problem of connectivity assessment of an asymmetric network represented by a weighted directed graph is investigated in this paper.

– The notion of generalized algebraic connectivity is introduced for this type of network as an extension of conventional algebraic connectivity measure for symmetric networks.

– This new notion represents the expected asymptotic convergence rate of a cooperative algorithm used to control the network.

– The proposed connectivity measure is then described in terms of the eigenvalues of the Laplacian matrix of the graph representing the network.

– The effectiveness of this measure in describing the connectivity of asymmetric networks is demonstrated by some intuitive and counter-intuitive examples.

– A variation of the power iteration algorithm is then developed to compute the proposed connectivity measure.

– To this end, the Laplacian matrix of the network is properly transformed to a new matrix such that existing techniques can be used to find the eigenvalue representing network connectivity.

Potential extensions

– The centralized algorithm proposed to compute the generalized algebraic connectivity can be extended to distributed implementation.

[C30] "A subspace consensus approach for distributed connectivity assessment of asymmetric networks"

Assumptions

– The weighted digraph representing the network is quasi-strongly connected.

– The Laplacian matrix of the network digraph has either a real dominant eigenvalue or a pair of complex conjugate dominant eigenvalues.

Main conclusions

– The connectivity assessment problem for an asymmetric network represented by a weighted directed graph is investigated in this paper.

– The notion of generalized algebraic connectivity for asymmetric networks is formulated in the context of distributed parameter estimation algorithms.

- The proposed measure is then defined in terms of the eigenvalues of the Laplacian matrix of the graph representing the network.
- A novel distributed algorithm based on the subspace consensus approach is developed to compute the proposed measure from the viewpoint of each node.
- The Laplacian matrix of the network is properly transformed such that the problem of finding the connectivity measure is reduced to the problem of finding the dominant eigenvalue of an asymmetric matrix.
- Two sequences of one-dimensional and two-dimensional subspaces are generated iteratively by each node such that either of them converges to the desired subspace spanned by the eigenvectors associated with the desired eigenvalues representing the network connectivity.

Potential extensions

- The proposed distributed algorithm can be employed in higher level problems to optimize the network connectivity and power consumption of the sensors.

[C31] "Simulation of communications based on underwater acoustic signals impaired by wide band attenuation"

Assumptions

- Attenuation (frequency and distance dependent) modelled by Thorp.
- Ambient coloured noise.
- Multipath propagation (reflection and refraction).

Main conclusions

- MATLAB and BELLHOP complement each other for the simulation of underwater acoustic data signals.
- MATLAB facilitates the implementation of the signal processing related features of the simulation, such as modulation and demodulation.
- BELLHOP is a software tool that addresses underwater multipath propagation of acoustic signals, taking into account environmental parameters such as bathymetry, sound speed profile, seabed type and sea surface type.

Potential extensions

- See related journal paper [B12].

[C32] "Location-free link state routing for underwater acoustic sensor networks"

Assumptions

- Underwater Acoustic Sensor Networks (UASNs) model. Network consists of a sink and sensors. All traffic is directed toward the sink.
- High bit error rate, low data rate and large propagation delay.

- Nodes do not know their geographical position and the sink position (location free).

Main conclusions

- Location-free link state routing protocol is applicable to UASNs.
- Characteristics of channels (hop count, path quality toward a sink and pressure) can be taken into account to avoid communication void problems.
- Routing strategy is loop-free and comprises a recovery mode that kicks in when network topology changes.

Potential extensions

- Include more physics-based underwater acoustics notions to this approach and re-evaluate.

[C33] "Simulation of underwater communications with coloured noise approximation and mobility"

Assumptions

- Attenuation (frequency and distance dependent) modelled by Thorp.
- Ambient coloured noise.
- Meandering current mobility model based on [Caruso 2008].
- Iso sound speed profile.

Main conclusions

- Mobility simulation is relevant because there are underwater vehicles and environmental conditions causing displacements of nodes. Because of mobility, transmitter-receiver separation distances are variable. Attenuation is sensitive to distance.
- Co-simulation, MATLAB and OMNeT++, can deal with software emulation of underwater acoustic digital data signal propagation, modulation, demodulation, mobility and integration of communication protocol layers.
- OMNeT++ is an excellent discrete event simulator with a modular programming interface that facilitates integration of new mobility models and network protocols, it lacks functionality to conduct the signal processing routines.
- MATLAB offers functionalities, such as modulator, demodulator of signals, filter, that, can be exported and integrated as an OMNeT++ module layer and above.

Potential extensions

- None.

[N87] "Toward hardware-driven simulation of underwater acoustic propagation and communication with Artic ice, wind waves, and currents"

Assumptions

- Use the BELLHOP ray tracer at its core.
- Included the effect water currents, sea surface, and a realistic ice keel profile.

Main conclusions

- Sound field under a partial ice cover is such that energy propagates in spatial ribbons.
- It seems that the ice canopy introduces a lot of steep angle propagating rays.

Potential extensions

- Write a journal paper with Monte-Carlo results now that the entire system is fully operational.

[N90] "Low power beamforming for underwater acoustic sensing using a 5-element circular hydrophone array"

Assumptions

- First-order and planar beamformer only requiring an omni, cosine and sine channel to produce a beamformed output.

Main conclusions

- Over a frequency band from 2 to 9 kHz, the output of the beamformer remained frequency flat with only minor deviations from the ideal pattern.
- The beamformer can be used to reduce, or even null out, multipath arrivals coming from different directions.

Potential extensions

- None.

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Underwater surveillance is inherently difficult because data transmission is limited and unpredictable when targets and sensors move around in the communication-opaque undersea environment. This report summarizes a three-year research project finding inspiration in Nature's collaborative tasks, such as wolves hunting in packs, to advance undersea-surveillance. The research proposes an unsupervised surveillance concept aimed at maximizing target localization and sensor covertness. This research project leverages recent technological advances to address two unique undersea challenges: intermittent communications and dynamic environmental changes. This document first reviews the scientific objectives and engineering challenges pertaining to these research activities before discussing impacts, results, and future challenges.

La surveillance sous-marine est intrinsèquement complexe dû au fait que la communication et la transmission de données sont restreintes et imprévisibles en présence de capteurs et de cibles faisant preuve de mobilité. Ce document présente un sommaire d'un projet de recherche d'une durée de trois ans et s'inspirant de diverses tâches de collaboration communes dans la nature, telle la chasse collective d'une meute de loups, afin d'avancer l'état de l'art en surveillance sous-marine. Ces efforts de recherche exploitent de récentes avancées technologiques tout en visant à compenser deux caractéristiques propres à l'environnement sous-marin, soit la présence de communications intermittentes et des changements environnementaux fréquents. Cette documentation rapporte également les objectifs scientifiques ainsi que les défis technologiques associés à ce projet de recherche avant de discuster les résultats, les divers impacts, et les défis futurs.