Institution: University of Southampton		
Unit of Assessment: 17 Business and Management Studies		
Title of case study: 17-07 The economic and geopolitical impact of improved risk management for marine autonomous vehicles		
Period when the underpinning research was undertaken: January 2008 – September 2017		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Mario Brito	Research Fellow; Associate Professor in Risk Analysis and Risk Management	January 2008 – March 2010; October 2015 – present
Gwyn Griffiths	Professor in Underwater Systems	October 2000 – November 2012
Period when the claimed impact occurred: October 2015 – July 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Through collaborations with world-leading manufacturers of unmanned vessels and the Canadian Government, University of Southampton (UoS) research on the risk and reliability of marine autonomous systems has resulted in economic and geopolitical impact.

UK company ASV Ltd embedded UoS's probabilistic modelling in the development process for its autonomous surface vehicles. This allowed ASV to meet the risk and safety levels required to:

- break into the profitable oil and gas market, securing a large market share;
- invest GBP500,000 in a new risk and reliability department;
- create two new high-skilled jobs; and
- form collaborations with industry leaders Thales and Shell.

For ASV's customers, the likelihood of an abortive mission, at a cost of several millions of pounds, was significantly reduced. ASV was subsequently acquired by a large US corporation; its risk management systems, based on UoS research, are now a core component of the corporation's proprietary technology.

The research enabled the gathering of fundamental evidence underpinning a 2019 landmark submission to the United Nations by the Canadian Government to extend its continental shelf. The scientific robustness of the submission is key to Canada's bid to increase its total land area by 10% and open up new resource exploration opportunities.

2. Underpinning research

Autonomous surface and underwater vehicles are increasingly used to explore hazardous or challenging marine environments. Research conducted over nine years at UoS by Dr Mario Brito (Southampton Business School) and Professor Gwyn Griffiths developed novel risk models to quantify and manage risk in the operation of marine autonomous systems.

Beginning in 2008, the research focused on assessing the risk of autonomous underwater vehicles (AUVs, i.e. submersible drones) experiencing system failure in polar seas. Specifically, Brito and Griffiths sought to develop a numerical model that could estimate the probability of NERC's Autosub3 AUV surviving a set of missions under Pine Island Glacier in Antarctica; the Autosub3's mission was to map underneath the glacier to determine its melt rate (**Grant 1**).

Prior to their maiden missions in Antarctica, AUVs operated in benign environments, for example in 'open water', where telemetry of data is possible. In Antarctica, where missions are carried out underneath ice, the AUV's position underwater is unknown. A fault that occurred in a benign environment may or may not lead to AUV loss in Antarctica. Reliability models available during **Grant 1** did not allow for an estimation of the probability of AUV loss because they relied on binary data; for an AUV, this would comprise either 'AUV lost in a mission' or 'AUV not lost in a mission'. Furthermore, these data did not exist because AUVs had not yet been deployed on enough occasions in Antarctica to record a sufficient number of 'lost' or 'not lost' missions.

To resolve this, Brito and Griffiths developed a risk model based on the *Kaplan-Meier* survival estimator – a statistical method for estimating survival probability as a function of time. It is most commonly used in medical research to measure the proportion of patients living for a certain amount of time after treatment. The Brito and Griffiths model took as its inputs: a) the history of faults collected during an AUV's missions in benign environments; b) a formal process of eliciting judgments from world experts in AUV design and operation on the probability of each of these faults leading to AUV loss in the target environment; c) the distances of successful missions. The resulting 'subjective survival estimator' was published in the *Journal of Risk Analysis* [**3.1**].

In April 2010, Brito joined NERC following its acquisition of the National Oceanography Centre but continued as a visiting researcher at UoS. Through a NERC project [**Grant 2**; 2011-2012], Brito and Griffiths further developed the subjective survival estimator model, modifying the way in which expert judgement was inputted. In **3.1**, they had used a mathematical approach to elicit expert judgements, where AUV experts were kept separate and provided individual assessments, and their views were combined to represent a group view. To minimise bias, they adopted a Bayesian behavioural approach, where AUV experts were brought together (in Canada, 2010-2011) to reach a consensus on the distributions of risks for faults or incidents [**3.2**, **3.3**]. Pre-mission predictive data and post-mission field data were used to assess the reliability of experts in estimating probability of failure mitigation [**3.2**, **3.3**]. These approaches demonstrated a 24% reduction in the probability of losing an AUV for a single mission of 336km [**3.2**]. Under **Grant 2**, Brito and Griffiths also developed a formalisation to update the risk profile for an AUV, based on the probability of failure prevention and correction, and the number of subsequent deployments on which the failure does not occur [**3.4**]. This used the *ISE Explorer* AUV as a case study (2010-12); this AUV was operated in the Arctic to gather evidence to support Canada's claim to extend its territory beyond 200 nautical miles from its shore.

This body of research underpinned a Knowledge Transfer Partnership (KTP) between UoS and Autonomous Surface Vehicles (ASV) Limited (**Grant 3**; 2015-2017). Brito was PI, having rejoined UoS on a full-time basis. The aim of the KTP was to embed a novel risk and reliability management capability within the company's range of autonomous surface vehicles. Methods developed by Brito to integrate the subjective survival estimator with Markov chains [**3.5**] and Bayesian networks [**3.6**] were transferred to ASV and applied initially to ASV's *C-Worker 5*, an unmanned survey vessel, and then new generations of the C-Worker.

Figure 1. C-Worker 5 demonstration at US Hydro 2017. Source L3Harris ASV (then ASV Global)

3. References to the research

3.1 Brito, M., Griffiths, G., & Challenor, P. (2010). Risk Analysis for Autonomous Underwater Vehicle Operations in Extreme Environments. Risk Analysis, 30(12), 1771-1788. https://doi.org/10.1111/j.1539-6924.2010.01476.x

3.2 Brito, M., Griffiths, G., Ferguson, J., Hopkin, D., Mills, R., Pederson, R., & MacNeil, E. (2012). A Behavioral probabilistic risk assessment framework for managing autonomous underwater vehicle deployments. Journal of Atmospheric and Oceanic Technology, 29(11), 1689-1703. https://doi.org/10.1175/JTECH-D-12-00005.1

3.3 Brito, M.P. and Dawson, I.G.J. (2020). Predicting the Validity of Expert Judgments in Assessing the Impact of Risk Mitigation Through Failure Prevention and Correction. Risk Analysis. https://doi.org/10.1111/risa.13539

3.4 Brito, M., & Griffiths, G. (2018). Updating autonomous underwater vehicle risk based on the effectiveness of failure prevention and correction. Journal of Atmospheric and Oceanic Technology. https://doi.org/10.1175/JTECH-D-16-0252.1

3.5 Brito, M., & Griffiths, G. (2011). A Markov Chain state transition approach to establishing critical phases for AUV reliability. IEEE Journal of Oceanic Engineering, 36(1), 139-149. https://doi.org/10.1109/JOE.2010.2083070

3.6 Brito, M., & Griffiths, G. (2016). A Bayesian approach to predicting risk of loss during Autonomous Underwater Vehicle missions. Reliability Engineering & System Safety, 146(2), 55-67. https://doi.org/10.1016/j.ress.2015.10.004

Underpinning grants

Grant 1 (2008-2012) NERC's Oceans 2025 Research Programme, work-package 8.4 Towards Targeted Reliability, contributing with the development of statistical survival estimators for quantifying the probability of mission abort and of vehicle loss in light of historical data and expert judgments on the consequence of each fault [**3.1**, **3.5**, **3.6**].

Grant 2 (2011-2012) Co-Researcher in NERC funded Tracking AUV risk mitigation, GBP65,000 contributing towards the development of a probability model for updating the risk profile in light of the effectiveness of the failure mitigation [**3.2, 3.3, 3.4**].

Grant 3 (2015-2017) Innovate UK KTP Marine Autonomous Systems Risk and Reliability, GBP166,000 contributing to the development of data collection processes and implementation of the statistical survival models for mission risk prediction, development of fault trees for C-Worker 5 ASV for quantifying the probability of mission abort.

4. Details of the impact

The University of Southampton's research-based risk models have significantly improved the safety and reliability of marine autonomous systems. This resulted in economic impact through direct commercial benefits to a UK-based company that was later acquired by a large US corporation, and via the supply of market-leading unmanned vessels and associated software to the oil and gas and defence sectors. Furthermore, the research made a key contribution to Canada's geoscience-based submission to the United Nations to extend its continental shelf beyond 200 nautical miles in the Arctic Ocean, and increase the country's land area by more than 10%.

Economic impact delivered through the KTP with ASV Ltd

The global autonomous ship and ocean surface robot market is expected to generate USD3.48bn in revenues during the period 2024-2035, according to the Department for Business, Energy and Industrial Strategy. Prior to the start of the KTP in 2015, the majority of ASV's missions were to support Royal Navy target practice and its unmanned vessels were designed to be used for four-hour periods only [**5.1**, **5.2**]. ASV used the KTP to translate UoS's risk and reliability modelling into innovative risk mitigation strategies to minimise the likelihood of costly premature mission abort [**5.1**]. This was key to ASV meeting its ambitions of breaking into the oil and gas and marine science sectors [**5.1**]; to sell products into these markets, ASV needed to demonstrate that they could meet the required safety and reliability standards. UoS risk management processes were applied to ASV's *C-Worker 5*, a multi-purpose marine surface vehicle, for which a failure model was developed and implemented [**5.2**]. This model '*identified weaknesses in its design and surrounding process documentation on implementation and training, for example the emergency stop system*' [**5.1**]. ASV were able to correct these weaknesses and optimise the design of the *C-Worker 5* and its other *C-Worker* models [**5.1**].

<u>Enabling access to new markets and revenue streams</u>

ASV's adoption of Brito and Griffiths' risk modelling methods allowed the company to enter new markets including oil and gas exploration, providing it with a competitive advantage in the marine autonomous systems sector [**5.1**, **5.2**]. As of late 2019, 50% of ASV's missions were being performed in industry settings; prior to the KTP in 2015 the majority of missions were for defence purposes [**5.1**]. This is significant in the context of ASV's annual turnover of GBP10m recorded in 2018 at Companies House. Without the UoS research-based contribution to building the safety case for ASV's unmanned vehicles, according to ASV's engineering director '*it would have been difficult to conduct the missions that we are conducting today as our vehicles must meet regulatory safety requirements*' [**5.1**]. He continued: '*Due to the KTP project led by Dr Brito, we are now able to have confidence that our unmanned vehicle's safety systems, such as the emergency stop, meet the required safety integrity level (SIL). This has facilitated our collaboration with clients in the Oil and Gas and Defence industry* [**5.1**].'

<u>New capabilities and employment</u>

The development of failure models under the KTP project led ASV to identify the need for additional staffing resources and new system capabilities [**5.1**, **5.2**]. A safety system for collision avoidance had to be defined and software reliability demonstrated. The company recruited a safety engineer with knowledge of specific industry safety standards, and a software safety engineer. New software tools, data collection processes and analysis methods were developed and are still in use [**5.1**, **5.2**]. They allow the company to describe the mission survival profile and quantify the likelihood of mission abort or vehicle loss [**5.1**, **5.2**].

<u>Commercial benefits for industry and wider economic impact</u>

The capital cost of an autonomous system is in the order of GBP500,000. However, the cost of a platform loss or aborted mission is in the order of several millions of pounds. The task of laying an oil or gas pipe in the seabed costs tens of millions of GBP per day. The C-Worker role is to identify the exact location of the pipe on the seabed, using acoustic sensors [**5.3**]. If the C-Worker ceases to operate, it can lead to the disruption of the mission and losses of millions of pounds. The failure model developed by Brito and Griffiths enabled engineers to review most critical failure modes prior to system development, allowing ASV to deliver a reliable product to their clients.

The model has also been applied in vessels developed by high-profile industry partners of ASV, the most notable examples being *Thales* and *Shell,* with demonstrable success. Thales UK use a modified version of ASV's *C-Sweep USV* primarily for minesweeping, named the *Halcyon* USV [**5.4**]. In 2016, Thales sought an upgrade to the Halcyon, including the risk management processes developed at UoS. The risk analysis research undertaken by Brito and Griffiths played a crucial part in the discussions of the upgrade. Their failure model was incorporated into the Halcyon, which subsequently completed the first completely autonomous crossing of the English Channel in 2018 [**5.5**].

During the course of the KTP project, ASV was invited to prepare a bid with Shell to develop an unmanned seismic energy source vessel for oil and gas exploration. This led to an unmanned offshore seismic survey near the deepwater Gulf of Mexico [**5.6**].

ASV described the research by Brito and Griffiths as '*a crucial contribution in terms of making significant improvements to the ongoing safety and reliability of Autonomous Surface Vehicles, which has resulted in continued growth in outputs*' [**5.1**]. In September 2018, a year after the end of the KTP, ASV was acquired by large US firm, L3 Technologies (annual revenues of USD9.6bn at the time) [**5.7**]. In 2019 L3 Technologies merged with Harris Corporation and was renamed L3Harris Technologies (USD17bn in annual revenues). The safety systems shaped by UoS research are a core component of the L3Harris' trademarked ASView Control System, which is deployed across the company's range of autonomous surface vehicles [**5.7**].

Impact on Canada's UN application to extend its continental shelf

On 23 May 2019 the Government of Canada, following an 11-year process, made a landmark submission to the Commission on the Limits of the Continental Shelf (United Nations Convention on the Law of the Sea, UNCLOS) to delineate Canada's extended continental shelf [**5.8**]. Canada provided scientific evidence that its continental shelf extends beyond 200 nautical miles, laying claim to an addition of 1.2 million square kilometres to its total land area of 9.98 million square kilometres [**5.9**]. This would allow Canada to explore and extract mineral and other nonliving resources from the seabed and subsoil. The research by Brito and Griffiths made a significant contribution to the collection of the geological seabed data that was required for a robust evidence-based submission to the UN [**5.10**, **5.11**].

A joint team comprising Canadian company International Submarine Engineering (ISE) Ltd, Defence Research & Development Canada (DRDC) and National Resources Canada (NRCAN) built two specialist AUVs to gather this data; the vessels were required to spend up to 72 hours under thick ice so any critical failure would have almost certainly resulted in highly costly vehicle loss [**5.10**, **5.11**]. Through direct input from Brito and Griffiths at specially convened workshops, the AUV team used the UoS *subjective survival estimator* to develop and validate a quantitative risk analysis for the *ISE Explorer* missions [**5.10**]. According to the ISE Explorer team, without the work of Brito and Griffiths, the operation team would not have known: 1) the importance of test missions in order to achieve the required reliability for mission success; 2) the most important failure modes to correct prior to the arctic mission; 3) the length of the initial monitoring distance at the beginning of a mission to achieve the acceptable risk level for AUV loss; 4) the risk of AUV loss for each of the seafloor mapping missions [**5.11**]. This '*key insight*' allowed the ISE Explorer team to revise their deployment strategy resulting in '*100% successful AUV missions*' and '*a more scientifically substantive submission to the UN*' [**5.10**]. ISE Ltd, a world leader in the design of autonomous vehicles, reported that they '*still use the philosophies and lessons learned from Dr Brito and Professor Griffiths to improve the reliability of [their] systems* [**5.10**].' The UN is likely to take several years to consider Canada's submission.

5. Sources to corroborate the impact

5.1 Testimonial letter from the Engineering Director of ASV.

5.2 ASV KTP Final Report.

5.3 L3 Harris webpage: https://www.l3harris.com/all-capabilities/c-worker-5-asv. The main differences between C-Worker 5, 7 and 8 are the type of payload and the operation environment. C-Worker 8 is for oil and gas operations. This requires the vehicle to meet more stringent health and safety requirements.

5.4 Details of the *C-Sweep* and *Halcyon* USVs: http://www.navaldrones.com/C-Sweep.html

5.5 https://www.thalesgroup.com/en/united-kingdom/news/thales-crosses-milestone-sea

5.6 ASV, Shell in unmanned seismic vessel project push, July 2017. https://www.offshore-energy.biz/asv-shell-in-unmanned-seismic-vessel-project-push.

5.7 Corroboration of the acquisition of ASV Ltd and the inclusion of safety system capabilities in L3 Harris' proprietary ASView Control system technology: https://www.businesswire.com/news/home/20180924005437/en; https://www.l3harris.com/all-capabilities/asview-control-system

5.8 United Nations Oceans & Laws of the Sea – Continental Shelf Submission by Canada.

5.9 Corroboration from the Canadian Government of the significance of its continental shelf submission to the UN: https://www.nrcan.gc.ca/simply-science/extending-our-outer-limits-canadas-2019-arctic-ocean-continental-shelf-submission-united-nations/22165

5.10 Testimonial letter from Senior Research Systems Engineer and Manager in Development at International Submarine Engineering Ltd. (ISE Ltd).

5.11 Testimonial letter from former Head of MAPS, Defence Research & Development Canada.