Institution: The University of Birmingham

Unit of Assessment: B13 – Electrical and Electronic Engineering, Metallurgy Electronic, Electrical and Computer Engineering submission

Title of case study: *SubSafe* - Games-Based Simulation to Improve Submarine Safety Training.

1. Summary of the impact

SubSafe is a high-fidelity, real-time interactive simulation of a Royal Navy (RN) submarine. The *SubSafe* programme has improved the delivery of spatial awareness and safety training for RN recruits, over and above legacy practices (such as PowerPoint, "chalk-and-talk" and technical manuals). It has also played a major role in influencing industrial and defence agency uptake of simulation technologies across a range of applications. UK (MoD), Australian and Canadian national strategies relating to future exploitation of simulation in training and concept visualisation have been positively influenced by the success of this programme. *SubSafe* has also been instrumental in launching a new, innovative games-based simulation company.

2. Underpinning research

The *SubSafe* research programme set out to investigate if interactive 3D, or "Virtual Reality" (VR) representations of a nuclear submarine could generate significant improvements in early spatial awareness training over and above that provided by more conventional forms of delivery media. Experiments were conducted to assess the spatial awareness acquired by RN students during VR training and the extent to which that awareness was transferred from the classroom to a real submarine. Secondary aims of the research involved evaluating different interactive techniques for delivering the VR material ("passive", or instructor-led, using a data projector, *vs*. "active", allowing each student "hands-on" with the simulation via laptops) and to assess students' and instructors' attitudes (and any change in attitudes) regarding the use of novel interactive technologies in RN training contexts. The *SubSafe* research is also relevant to the training of spatial awareness or health and safety issues for other complex engineering contexts, including land-based and offshore petrochemical and gas plant, nuclear and mining facilities, and civilian maritime transportation.

Early Human Factors observations and task analyses supporting the design of the *SubSafe* VR system and its integration into existing training régimes were conducted (a) within the Submarine Qualification (SMQ) classrooms at HM Naval Base at Devonport, (b) onboard *Trafalgar* Class submarines alongside and (c) at sea with the crew of HMS *Tireless* (References 1, 4 and 6 in Section 3). Uniquely, *SubSafe* was the first games-based training system of its kind to receive a thorough experimental evaluation, based on nearly 24 months of investigation using real submarine recruits in real naval classroom and vessel settings. Statistical analyses of knowledge transfer data revealed that use of *SubSafe* during classroom training significantly improves the final "walk-around" performance of students (onboard an actual submarine) when compared to that of a control group receiving legacy training techniques (References 3 and 5 in Section 3). No significant differences in onboard spatial awareness were found between passive and active presentations of the simulation. Further experiments have investigated the optimum presentation times for *SubSafe*, comparing a single exposure of the simulation to SMQ students at the end of their 6-week training régime to course-specific exposures during weeks 2 to 4 (Reference 5 in Section 3). Significant attitudinal changes were also recorded after exposure to *SubSafe*, with participants responding positively to the use of games-based simulation in mainstream RN training (References 3 and 5 in Section 3).

From an **international perspective**, *SubSafe* is a successful example of a games-based training project that has benefited from a detailed academic approach to design and evaluation from the outset. The result of over ten years of exploratory research (beginning with pioneering complex engineering data conversion techniques for real-time interaction in the early 1990s), *SubSafe* has included investigations of:

- the human-centred design of interactive visualisation or VR techniques for representing detailed plant and machinery spaces whilst preserving real-time computer rendering performance (Reference 6 in Section 3),
- new processes for optimising engineering data and integration of said data with other interactive media (3D computer-aided design, 2D panoramic photography, photogrammetry, etc.)

- new simulation/VR sensory fidelity research, building upon the capabilities of commercial off-the-shelf gaming toolkits and rendering engines (e.g. dynamic interior lighting, physics-based incident effects, such as smoke and flooding),
- new usability/human factors research relating to end user 3D navigation requirements and interrogation of/interaction with important or safety-critical virtual objects (Reference 6 in Section 3 – specifically Case Studies 8 and 9), and
- human factors issues of preserving spatial awareness knowledge uptake when providing minimised virtual representations of submarine spaces suitable for portable computing technologies (e.g. tablets – with minimal degradation to fidelity and real-time interaction, *SubSafe* has been implemented on such products as the *iPad*, *iPhone*/*iPod* and *Nexus 7*).

SubSafe was sponsored by the MoD via the Human Factors Integration Defence Technology Centre (HFI DTC). This DTC was a highly successful national centre of excellence in which the University of Birmingham was a key collaborator, receiving a total of £4.5million between 2003 and 2012 for a range of research and technology evaluation studies (see also Reference 6 in Section 3). Although the *SubSafe* research can be traced back to early (1990s) RN submarine research and concept development projects conducted by Stone (Professor of Interactive Multimedia Systems at Birmingham, March 2003 onwards), the effort reported here was undertaken between 2008 and 2012 by Stone and Guest (Research Fellow at Birmingham, October 2007 onwards) with additional contributions from Caird-Daley (Research Assistant, Cranfield University).

3. References to the research

The outputs that best indicate the quality of the underpinning research are references 3.1, 3.3 and 3.5

1. Stone, R.J., Caird-Daley, A., & Bessell, K. (2009). "*SubSafe*: A Games-Based Training System for Submarine Safety and Spatial Awareness"; *Virtual Reality*; 13(1); pp.3-12. *DOI: 10.1007/s10055-008-0110.* Listed in REF 2.

2. Stone, R.J. (2009). "The Safe Submariner", *Armed Forces Worldwide*; Vol 2. *Available from HEI*.
3. Stone, R.J., & Caird-Daley, A. (2009). "Submarine Safety and Spatial Awareness: the *SubSafe* Games-Based Training System"; in *Proceedings of the Ergonomics Society's 60th Anniversary Conference*; Royal College of Physicians; London; 23 April 2009; pp.320-331. *Available from HEI*.
4. Stone, R.J. (2010). "Serious Games – the Future of Simulation for the Royal Navy?"; *Review of Naval Engineering*; 3(3); pp.37-45. *Available from HEI*.
5. Stone, R.J., Caird-Daley, A., & Bessell, K. (2010). "Human Factors Evaluation of a Submarine Spatial Awareness Training Tool" (with Caird-Daley and Bessell); In *Proceedings of the Human Performance at Sea 2010 Conference*; Glasgow, 16-18 June; pp.231-241. *Available from HEI*.
6. Stone, R.J. (2012). "Human Factors Guidance for Designers of Interactive 3D and Games-Based Training Systems" (Second Edition); Human Factors Integration Defence Technology Centre Publication; February, 2012. Case Studies 8 and 9. *Available from HEI*.

4. Details of the impact

The key to the success of *SubSafe* has been the demonstration of innovation in technology-based training for complex engineering systems, with specific reference to the submarine training sector, where the increasing "absence" of submarines alongside at naval bases (due to streamlining in the Armed Forces and the development of more advanced naval platforms) would otherwise have a negative impact on RN recruits' knowledge uptake and retention. This situation is unlikely to change in the coming decades as the sizes of current-generation submarine fleets reduce and fewer, more advanced vessels (such as the UK's *Astute* and *Successor* classes of submarine) come into service.

The same situation exists within international navies, such as Canada and Australia, where future submarines (and, indeed, surface vessels), although technologically highly advanced, will be smaller in number and will remain at sea for much longer periods than is currently the case. The results of the *SubSafe* experimental programme have demonstrated (not only to the RN, but to interested senior observers from the Royal Canadian and Australian Navies as well) that SMQ students are likely to benefit significantly from games-based training, even in the absence of

submarines alongside, and such training will improve their familiarisation and, thus, their safety awareness when they are eventually exposed to real, complex submarine spaces and systems.

UK Adoption/Impact. As well as the installation of *SubSafe* into the Waterfront Learning Centre at HM Naval Base, Devonport in April, 2011, the results of the *SubSafe* programme were influential in the establishment, at HM Naval Base, Faslane, of a new training facility developed by Babcock International for the *Astute* Class submarine (again in 2011). Feedback from the operators of this facility indicate that, from the first four courses undertaken, all 80 students passed the SMQ process first time, and follow-up investigations show that the time taken for subsequent on-the-job (consolidation) training is significantly less than that given to other submarine trainees who have received more conventional forms of training. Although specific financial savings cannot be released due to MoD and commercial sensitivities, the Babcock training team (as emphasised in Letter 1 from the company's Submarine Training Director) believes that 400 man weeks per year is being saved as a result of adopting technology–based training as developed during the *SubSafe* programme. Babcock has put an agreement into effect, enabling the University of Birmingham to provide human factors and simulation consultancy for its future submarine training programmes.

Government/Policy Impact. At a government agency strategic level, and acknowledged at Admiral level, including Flag Officer Sea Training (FOST), the *SubSafe* programme has also provided inputs into RN policy (Letters 2 and 3). *SubSafe* has influenced the MoD's Submarine Training & Education Programme, STEP, and the future adoption of simulation and virtual environments to support submarine design and training, including the establishment of a dedicated SUBFLOT (Submarine Flotilla) Team to determine future submarine capabilities. STEP is a combined MoD, RN and industry team set up to optimise training and education to sustain the UK's nuclear defence capability. The STEP Team is also planning to set up a UK Submarine Enterprise Academy, which would be another exploitation path for the *SubSafe* project. In addition to the STEP development, the University of Birmingham has also been recruited to provide specialist simulation know-how to Dstl, as part of their Future Submarine Command Space R&D Programme.

SubSafe was also one of two success stories cited in the 2011 MoD Chief Scientific Advisor's Commendation, presented to Stone in recognition of excellence in defence science and technology (CSA Citation Text). Peter Luff MP, Minister for Defence Equipment, Support and Technology, subsequently wrote to Stone in support of this and commending *SubSafe* as addressing the "significant challenge of submariner training" (Letters 7 and 8).

International Impact. The results of the *SubSafe* programme have also been exploited by international navies to justify developing their own virtual SMQ training packages. Both the Royal Australian and Canadian Navies have acknowledged the important role played by *SubSafe* in their evolution of similar technologies for their own submarine fleets. Letters 4 and 5, for example, from senior training figures in the Royal Australian and Canadian Navies, include comments such as "The usefulness and practical employment of the SubSafe program was impressive; we will use the experience and information to refine our product, to achieve the knowledge transfer that we seek"; "(the) *SubSafe* virtual submarine project has greatly inspired the Royal Canadian Navy Learning Support Center in pursuing the development of the Canadian Virtual Naval Fleet Project"; and "The lessons learned from your project provided our personnel with expertise that really facilitated our decision to use PC based virtual environments to support spatial and system awareness training and also greatly oriented our design and development process."

***SubSafe* Simulation Re-Use.** Another key element in the impact success of *SubSafe* has been the early attention paid to the design of the 3D media to support rapid re-use for related training and visualisation opportunities. As a result, related industrial impacts have been evident with other future Royal Navy vessel programmes, where early concept designs have exploited the tools developed by the University and lessons learned from the *SubSafe* programme. These include the Type 26, or *Future Surface Combatant* (coordinated by the Naval Design Partnership) and *Successor*, the future submarine (coordinated by BAE Systems). Other safety training demonstration projects based on *SubSafe* and presented to the Royal Navy have included a disabled submarine rescue simulation and an ergonomics study of the deployment of CO_2-absorbing Lithium Hydroxide "curtains" within the Forward Escape Compartment. These examples have also provided the Birmingham Research Team with a range of assets, tools and techniques suitable for application in other defence and civilian engineering contexts, such as those mentioned

in Section 2.

Exploitation – RN Court Hearing. Another example of effective early design for media re-use and exploitation was the modification of *SubSafe* to provide a world first animation sequence for legal proceedings at a Coroner's Court of Inquiry in 2009. Presented by the (then) Commanding Officer of the Britannia Royal Naval College, Commodore Jake Moores, the animation sequence related to an incident onboard the British nuclear submarine HMS *Tireless* in March 2007 (also mentioned in Letters 2 and 3). Whilst conducting under-ice exercises north of Alaska, and during what should have been a routine lighting of a Self-Contained Oxygen Generator (SCOG), the unit exploded, resulting in two fatalities and one serious injury.

Company Formation and Awards. The *SubSafe* project led to the formation and launch, in 2009, of an innovative micro-small-to-medium-sized enterprise, MODUX, to provide 3D modelling and simulation support to the University of Birmingham Team (during the transition of the early research output into a more "productised" version – *SubSafe 2* (Letter 6)). This company is still (2013) actively involved with the University VR team in such areas as simulation for Counter-Improvised Explosive Device Awareness Training and future explosive ordnance robotics simulation. Along with the Birmingham Team, MODUX (and Cranfield University) received the BAE Systems Chairman's Bronze and Silver Awards in 2011 for achievements relating to (amongst others) the *SubSafe* project.

Additional Dissemination. The *SubSafe* project features in a BBC educational TV series – *The Designed World* – which focuses on engineering and the social impact of design and technology (http://www.bbc.co.uk/programmes/p011n89f). Finally, the Case Study forms an important part of a booklet entitled *Human Factors Guidance for Interactive 3D and Games-Based Training Systems Design* (Reference 6 in Section 3), 1500 copies of which were published in 2012 (MoD-sponsored) for free national and international distribution (industrial, academic and government), in addition to on-line access (at www.birmingham.ac.uk/stone).

Concluding Statement. *SubSafe* is an example of how human-centred research conducted during both the early design and, later, experimental evaluation stages of a very new interactive software concept, can lead to significant real-world uptake, impact and influence on a wide-reaching scale, from UK and international industries to national and foreign government policy makers and safety-critical training providers. The research has also been influential in helping to overcome many of the negative perceptions of VR-based R&D endeavours, brought about by the "technology push" biases and associated failures evident in the 1990s/early 2000s (Reference 6 in Section 3).

5. Sources to corroborate the impact

1. Submarine Training Director, Babcock International Group, Astute Training Facility, HMNB Faslane. **LETTER 1**
2. Flag Officer Sea Training, FOST & Director Submarines, MoD Defence Equipment and Support **LETTERS 2 and 3**
3. Can be contacted for corroboration: Senior Business Interface Manager, BAE SYSTEMS - Submarine Solutions, Barrow-in-Furness. (impact on submarine training, Royal Navy)
4. Can be contacted for corroboration: Challenger Institute of Technology contractor to ASC Pty Ltd at Training Authority Submarines, HMAS Stirling, Garden Island, Australia. (impact on Royal Australian Navy)
5. Can be contacted for corroboration: Staff Officer Simulation Training Technology Support Centre, HMAS Stirling, Garden Island, Australia. (impact on Royal Australian Navy)
6. Commander, Royal Australian Navy Training Authority – Submarines. **LETTER 4**
7. Director Maritime Training and Education,. Royal Canadian Navy **LETTER 5**
8. Can be contacted for corroboration: Navy Learning Support Center, Défense Nationale, Québec Canada. (Impact on Royal Canadian Navy)
9. Technical Director, MODUX Limited, Nottingham. **LETTER 6**
10. MoD Chief Scientific Advisor's Commendation Award http://www.science.mod.uk/codex/documents/codex_issue_9.pdf **,** page 3
11. Peter Luff MP, Parliamentary Under Secretary of State and Minister for Defence Equipment, Support and Technology. **LETTERS 7 and 8**