Manoeuvring Simulation of Multiple Underwater Vehicles in Close Proximity

Dr Adam Mawby
SEA (Group) Ltd
Beckington Castle
PO Box 800
Frome BA11 6TB
United Kingdom
Tel. +44 (0) 1373 852236
adam.mawby@sea.co.uk

Paul Wilson
QinetiQ Ltd
United Kingdom
Tel. +44 (0) 23 9233 5201
pnwilson@QinetiQ.com

Dr Marcus Bole
Graphics Research Corporation Ltd
United Kingdom
Tel. +44 (0) 23 92 334003
mb@grc-ltd.co.uk

SP Fiddes
Flow Solutions Limited
United Kingdom
Tel. +44 (0) 1454 880564
steve@flowsol.co.uk

Dr John Duncan
Defence Procurement Agency, TES-SSG-SBA
United Kingdom
Tel. +44 (0) 117 3229079
tes-ssg-sba@dpa.mod.uk

Abstract The Sea Systems Group, Simulation Based Acquisition (SSG-SBA) of the UK Ministry of Defence (MOD) Defence Procurement Agency (DPA) has identified a requirement to develop a capability for reusable simulations that model the interaction between underwater bodies. Two scenarios of particular interest are: an underwater body (UB) manoeuvring in the vicinity of a moving submarine; and a rescue vessel manoeuvring to and mating with the escape hatch of a distressed submarine.

The S29 Technology Demonstrator was produced by SEA in conjunction with Flow Solutions, GRC and QinetiQ. It addresses the first of the two scenarios mentioned above.

The simulation is implemented utilising the flexibility provided by the modular High Level Architecture (HLA). The motion of the underwater vehicles is subject to environmental effects including waves, current and water density gradients. The simulation comprises six unique underwater vehicle models, an environment model and a visualisation. The simulation runs successfully in real-time with all six vehicles operating simultaneously.
1 Introduction

This work was carried out by Systems Engineering & Assessment Ltd. (SEA), as Prime Contractor, and subcontractors Flow Solutions, GRC and QinetiQ, under the UK Ministry of Defence (MOD) Project VISTA Contract.

The Sea Systems Group, Simulation Based Acquisition (SSG-SBA) of the UK MOD Defence Procurement Agency (DPA), has identified a requirement to develop a capability for reusable simulations that model the interaction between underwater bodies. Two scenarios of particular interest are: an underwater body (UB) manoeuvring in the vicinity of a moving submarine; and a rescue vessel manoeuvring to and mating with the escape hatch of a distressed submarine. The S29 Technology Demonstrator, discussed here, addresses the first of these two scenarios but also provides a proof of concept for a reusable simulation architecture, which could address the second scenario and other underwater vehicle simulation challenges. An example of scenario one is illustrated in Figure 1–1.

![Figure 1-1 Underwater body manoeuvring in the vicinity of a moving submarine](image)

The motion of the simulated UB and submarine are subject to the environmental effects of waves, current and density gradients. For the S29 Technology Demonstrator the effects of the wake and turbulence flow fields generated by the submarine have not been modelled. The submarine does not therefore influence the UB motion.

The S29 framework provides a simulation environment for solving problems that cannot easily be solved by a single piece of monolithic code. It also provides a vehicle for the interoperation of models from different sources. The framework is suitable for addressing problems involving the interaction of multiple underwater vehicles, ships and cables. In such cases, MOD Integrated Project Teams (IPTs) will require S29 model suppliers to develop customised S29 models that meet the requirements of the problem space. These models may be developed under single tender action or competed, as deemed appropriate by the IPT. The customised models, being compliant with the S29 interfaces, will be plug and playable under the
S29 architecture. However, before this can be put into practice, there is a need for a proof of concept of S29 in the way of a Technology Demonstrator.

1.1 Objectives

The objective of the Technology Demonstrator is to prove the S29 concept and its architecture so that both may be re-used to solve specific engineering problems faced by IPTs.

The submarine and UB models are regarded as specific configurations of a generic underwater vehicle (UV). A submarine model will typically represent a large (e.g. nuclear) submarine, whereas a UB model will typically represent a much smaller vessel. With respect to the interface, all UV models are equivalent. S29 model suppliers will supply specific vehicle models conforming to the S29 interface. The primary outputs of the underwater vehicle model will be its 6-degrees of freedom motion, thruster revolutions per second, hydroplane angles and tank levels (if applicable).

The user will have the option to save and restore the state of the simulation at runtime. For example, during a simulation run there may be an event after which some interesting behaviour is expected where it would be useful to repeat the simulation from that event. It is also recognised that, without a state vector to restore from, it is not always possible to initialise the simulation with consistent data. Therefore, there are two modes by which the simulation may initialise itself, either by reloading a previously saved state vector, or by commencing afresh with initialisation data that may not be totally self consistent and then allowing the system to settle down to a consistent state, from which state vectors can then be saved.

2 Architecture

S29 is concerned with the creation of a distributed simulation architecture for studying the behaviour of underwater vehicles. The framework consists of software models that communicate with each other through a High Level Architecture (HLA) compliant interface. The architecture promotes interoperability on many levels. The HLA wrapper is separated from the simulation engine, with overall timing control and Real-Time Interface (RTI) communication being performed by the wrapper. The underlying simulation is packaged as a library (DLL), and communication between the wrapper and the simulation occurs via simple function calls (see Figure 2–1).

![Figure 2-1 S29 UV interface](image-url)
Although this approach does introduce an additional interface to manage, it has several advantages:

- Clear distinction between the system level issues and the specific domain issues.
- Removal of necessity of domain experts to acquire HLA knowledge.
- Preservation of security/IPR status of the underlying simulation via library packaging.
- Clean, modular decomposition of testing.

Figure 2–2 shows the basic framework components of an example simulation.

![Figure 2-2 S29 basic framework components](image)

The underlying submarine and UB models along with their RTI interfaces are referred to as a federates. A collection of federates forms a federation. A typical federation could include a UB federate, submarine federate, the environment federate, the visualisation federate and a federation manager (an optional extra that could maintain synchronisation when the simulation is run faster than real-time). Such a federation is represented below in Figure 2–3. However, the support federates (manager, environment and visualisation) are sufficiently flexible to allow any number of UV federates to join (and leave) the federation.
Figure 2-3 Typical federation
3 Modelling Solutions
Details of the underwater vehicle models, the environment model and the visualisation model are provided in the sections that follow.

3.1 Underwater Vehicle Models
The underwater vehicle modelling techniques and resultant models are discussed below. As specified by the S29 UV interface, all models contain closed-loop autopilots but no guidance. Vehicle control is via commands contained in configuration files read by the models. These commands are for depth, heading or speed change at a specified time.

3.1.1 Flow Solutions underwater vehicle models
The generic model uses a pre-processed form of the hydrodynamic results from the Flow Solutions NEWPAN code. The pre-processed data describes the hydrodynamic forces acting on a given vehicle at varying angles of attack and sideslip to a uniform flow and in the presence of environmental flow fields.

NEWPAN uses a boundary element method (often called a panel method) to solve Laplace’s equation for the inviscid, irrotational flow past a detailed geometrical model of the vehicle surface. The model allows for the effect of lifting components but assumes an attached flow; an empirical correction for the effects of gross separation is added to the basic NEWPAN result.

Although NEWPAN could be executed run-time at each time step, this is not currently feasible for a real-time simulation. Hence, a set of “base solutions” for particular onset flows (e.g. rigid body motions, non-uniform onset flow due to an oblique wave) are pre-computed as part of the model description contained in the configuration file. During execution these base solutions are combined to represent the total solution for the instantaneous flow and thence produce the instantaneous forces and moments.

A configuration file for both a submarine and an underwater body were supplied. The software used to produce these configuration files takes as input the vehicle body form and could be used to produce a configuration file for any given vehicle. The model includes a full depth and heading autopilot implementation, together with trimming tanks. Compressibility is also modelled as a function of depth.

3.1.2 QinetiQ underwater vehicle models
The basis for both the simulated model vehicles provided by QinetiQ is the coefficient based mathematical model developed at QinetiQ Haslar over a period of many years. This model is currently implemented as the QinetiQ simulation program SUBHOV, the supplied vehicle simulations comprising of a subset of the available SUBHOV functionality.

The two vehicle models share the same design and control behaviour, the only differences being in the different locations of tanks and different rates to reflect the difference in sizes of the simulated vehicles. Each vehicle includes a full depth and pitch autopilot implementation, together with trimming tanks. Compressibility of the submarine is also modelled as a function of depth.

3.1.3 GRC underwater vehicle models
The GRC model has been adapted from a generic submarine system model known as S4. The S4 simulation was developed by W.S. Atkins based on the AMTE Haslar equation set. The model is coefficient based and it is the coefficient values that are specified by the vehicle configuration. The delivered DLL remains generic and reads a configuration file containing the model coefficients. A configuration file for both a submarine and an underwater body were supplied.
The model includes a full depth and pitch autopilot implementation, together with trimming tanks. Compressibility is also modelled as a function of depth. The GRC UB model is a rescue vehicle and therefore slightly different in nature to the unmanned vehicles modelled by Flow Solutions and QinetiQ.

3.2 Environment Model

The environment model supplies any number of UV federates with environmental data for the requested sample points. The environmental data comprises current flow (including wave effects), water density and height above seabed values. The data is exchanged between federates using a client-server approach, described as follows:

- the federate publishes the dynamic state spatial data of the object and the sample points (in body centred coordinates) around the object at which it wants to sample environmental data;
- on receipt of the sample points and spatial data, the environment federate will calculate the data at the sample points and publish them for the requesting federate to act upon.

3.3 Visualisation Model

The visualisation can:

- display all of the objects within the federation;
- display 3D graphical representation of the vehicle motions;
- display surface waves for the marine environment;
- display the seabed.

The user is able to adjust the viewpoint of the visualisation at any time during simulation. The visualisation provides two mechanisms for doing this:

- fixed viewpoints, relative to the object or to the ground, will be defined within the configuration file; the default view will be able to be cycled through these viewpoints;
- free viewpoints, with the position of the eye and the camera modifiable by mouse control.

The visualisation provides a Head-Up-Display, or informational overlay, which supports visualisation of:

- tank levels;
- hydroplane motion;
- thruster RPM;
- vehicle position and orientation.

Two stills from the visualisation are shown in Figure 3–1, the first looking from below the vehicle and the second looking from above water.
Figure 3-1 Visualisation stills
4 Results
The concept of UV model interoperability has been proven.
- Six underwater vehicle federates have been provided, all conforming to the S29 interface.
- The simulation has been shown to run with all six underwater vehicle federates.
- Both the environment model and the visualisation model will detect UV federates as they enter the federation and respond accordingly.
- It is possible to save the simulation and perfectly restore at a later date from saved state data files. Alternatively the simulation can be started using initial condition data.
- Up to six underwater vehicle federates were able to maintain real-time performance when run simultaneously on a single standard specification PC.

5 Future Development
The S29 Technology Demonstrator has proven the concept of UV model interoperability. There are however a number of clear advances that can be made. These include:
- adding closed loop waypoint guidance to the UV models so that the vehicles can follow a pre-described waypoint specified mission;
- adding man-in-loop operation to UV models (of particular relevance to the UB models), the “man” could take visualisation cues from a dedicated “camera” visualisation;
- development of environment interface to allow for interaction between vehicles – this would most likely mean the environment providing forces and moments rather than flows.

Scenarios of continuing interest, to which the S29 Technology Demonstrator architecture and models could be applied, include:
- Unmanned underwater vehicles for vessel protection in ports and harbours: much of this involves mine search and disposal using autonomous unmanned underwater vehicles. SEA has extensive experience in this area from acting as prime contractor on the UK MOD funded Battlespace Access Unmanned Underwater Vehicle (BAUUV) technology de-risking project.
- NATO Submarine Rescue System (NSRS): this is the second of the two scenarios mentioned in Section 1, modelling a UB manoeuvring to and mating with the escape hatch of a submarine model. This application necessitates the modelling of the interaction between the two vehicles.

6 Conclusions
The S29 simulation has demonstrated model interoperability using an interface framework and underwater vehicle simulations produced by a range of subcontractors. As well as providing a set of reusable models, the framework can easily be expanded to encompass further vehicle types and configurations. The simulation environment is now ready for use to address design and operational questions relating to a range of multiple underwater vehicle scenarios.

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