Integrating the Spectre Autopilot into the Wayamba Research Platform

C. Madden, J. Gilbert and B. Knox

Maritime Platforms Division
Defence Science and Technology Organisation

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ABSTRACT

This report documents the successful integration of a commercial autopilot (a “Spectre” system from H-Scientific) into DSTO’s Wayamba unmanned underwater platform, which was tested in sea trials during November 2011. The Spectre is a closed loop controller that, once tuned and matched to a vehicle, affords independent control of vehicle parameters such as pitch, roll, heading and speed, as well as allowing more complex manoeuvres such as track following, hovering and lateral motion. The autopilot uses an automatic tuning process to set its control parameters, refining a user-provided allocation table representing the gross effects of the vehicle’s actuators on its motion. While the resulting control may not be provably optimal, this tuning process can take place without a detailed hydrodynamic model. In Wayamba’s role as a delivery system and testbed for large payloads, vehicle dynamics and response may change considerably between or even during missions. The Spectre allows tunings for various configurations to be stored and switched online, for example when a payload is deployed. As an illustration of the degree of control demonstrated in the trial results, the Spectre was able to keep Wayamba hovering for some 25 minutes with a standard deviation in position less than 10 centimetres, and a standard deviation in heading of less than one degree.

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Executive Summary

Unmanned and Autonomous systems are being used around the world to perform tasks which are too difficult, dangerous or require a higher degree of accuracy than humans can achieve. Defence forces are interested in utilising unmanned capabilities to both gather information and counter potential threats in the environment without exposing personnel during such potentially dangerous tasks.

DSTO has been building its experience in Automated Underwater Vehicle’s through its remotely operated Wayamba Platform. This report outlines how H-Scientific’s Spectre autopilot was successfully integrated into this platform to increase its level of automation using a commercially available system. The autopilot integration was conducted in three stages. The first stage utilised H-Scientific’s AUVsim product to simulate its control of Wayamba and familiarise the research team with the autopilot’s operation and control using the Remote Control Workstation (also a H-Scientific product) as its software interface. The second stage successfully tested the integration of the autopilot to accurately control Wayamba’s actuators in the limited space of DSTO’s indoor fresh water tank. The third stage of open sea trials successfully tested all of the autopilot’s control modes including the ability to follow a track at a set speed and to hover at a given location. These trials confirmed that operators using the autopilot software could more precisely maintain a given vehicle parameter or control mode with minimal operator interaction.

The Spectre was matched to the Wayamba vehicle by providing a basic actuator configuration, which was then refined using the unit’s automatic tuning process. After tuning, the autopilot allowed Wayamba to maintain vehicle parameters, such as heading and roll (pitch to a lesser degree), speed and depth, while also providing algorithms for more complex control regimes such as track following and hovering. In sea trials, precision control was immediately apparent in preliminary results, with the Spectre able to keep Wayamba hovering at a fixed location within 10cm for 25 minutes, and cross track error for straight line paths typically much less than one metre.

This work demonstrates that commercial autopilots of this type may be rapidly matched to an existing vehicle, using information about the configuration of actuators and an automatic tuning process, but without necessarily having access to a detailed hydrodynamic model. The same autopilot may be adapted to provide low-level control for a variety of possible unmanned maritime vehicles — or different configurations of the same vehicle — as an alternative to developing custom in-house controllers for each one. While not providing a fully autonomous system in a box, reliable low-level control is an important step towards true autonomy, and it appears that commercial autopilot technology, especially in the unmanned underwater vehicle domain, has progressed so that it is now possible for such control to be readily dropped in off-the-shelf for a range of platforms or platform configurations.
Authors

Christopher Madden

*Maritime Platforms Division*

Christopher Madden graduated from the Australian National University in 2003 with a BEng and a BIT. Christopher conducted a Ph.D. at the University of Technology Sydney in video surveillance focusing upon tracking individual people through multiple cameras. This research in object analysis and tracking was then applied as a part of Kingston University’s entry into the 2008 MOD Grand Challenge, a UK based robotics competition aimed at using automated systems to identify potential threats in a combat arena. Until 2010, Christopher worked at the University of Adelaide investigating projects ranging from large scale video surveillance to the MAGIC 2010 robotics competition, where coordinated groups of robots explore and identify key threats autonomously. He now works in DSTO’s Maritime Platforms Division conducting research into increasing the automation and sensor processing capabilities of unmanned vehicles, as well as methods for simulating the behaviour of such platforms.

John Gilbert

*Maritime Platforms Division*

John Gilbert completed an Advanced Diploma of Engineering Technology in Mechatronics and Robotics at Swinburne University in 2006, and is currently undertaking a BEng in Robotics at Deakin University. He has a diverse background, working mainly in the electromechanical domain, including remotely controlled mining equipment, power generation and building electrical automation systems. John joined DSTO’s Maritime Platforms Division in 2010 after completed a scholarship year at DSTO where he worked on design concepts for dispensable unmanned aerial vehicles for submarines.
Bradley Knox  
*Maritime Platforms Division*

Brad joined DSTO as a Research Scientist in 2005 after working as a software engineer with Boeing, developing what would become the WANE communications infrastructure for MPD's Wayamba vehicle. His research interests lie in the field of probabilistic robotics and within the Automation and Unmanned Maritime Systems Group he is responsible for sensing and navigation strategies for both simulated and existing UUVs. Brad studied pure mathematics at the University of Wollongong, graduating with honours in 1995. He went on to complete a PhD at La Trobe University studying duality theory, a branch of general algebra having links to topology and category theory.
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Glossary

**AUV** Autonomous Underwater Vehicle

**AUVsim** H-Scientific’s simulation environment for Automated Underwater Vehicles.

**CAM** Control Allocation Module - Spectre’s interface which allocates thrust to different machinery output channels

**COTS** Commercial off the shelf

**DCAM** Direct control allocation module input mode

**NMEA 0183** An industry standard for serial communication between marine electronic devices

**RCW** Remote control workstation

**SSSCP** H-Scientific’s proprietary remote control command protocol

**UUV** Unmanned underwater vehicle

**WANE** Wayamba Network Environment
1 Introduction

Unmanned systems are attractive for certain defence operations as they provide an increased capability to gather information and interact with the environment while limiting the exposure of personnel to risk or danger [1]. One area of maritime operations where such systems have a natural role is in the detection and disposal of sea-mines. The ADF is actively investigating future capability in this area through the SEA 1778 project.

The underwater environment poses a unique set of challenges for autonomous systems, over and above the inherent challenges of autonomy in general. Communications may be constrained to the very low bandwidth acoustic channel; exotic or expensive navigation techniques and systems may be required for positioning. The environment may be cluttered with unstructured, moving obstacles or may alternatively be completely devoid of features that could otherwise provide useful landmarks. These factors imply a general sense that for underwater robots to undertake operations of even very modest complexity, a relatively high degree of autonomy would be required.

This paper is the second in a series that details the implementation phases of integrating a commercial autopilot control system into DSTO’s Wayamba Unmanned Underwater Vehicle (UUV). Prior to this stage, Wayamba has been operated purely as a Remotely Operated Vehicle (ROV) with the pilot having essentially direct control of the vehicle’s actuators via an umbilical tether [2]. The inclusion of an autopilot based control system enables the vehicle to operate semi-autonomously by providing a range of automatic control options to provide accurate manoeuvring, further broadening its capabilities and flexibility. DSTO-TR-2696 [3] details the research that was conducted in identifying potential commercial autopilots and identified the Spectre autopilot, sold by H-Scientific, as a good candidate for integration into Wayamba. This particular autopilot utilises a closed loop control system, which receives data about the current vehicle location and pose in order to determine the amount of actuator output required to achieve a certain control mode’s set point or desired behaviour. Where multiple control modes are applied, then the outputs to the actuators will be a combination of the commands required to reach each of the set points, allowing independent control of aspects such as heading and depth.

In this second phase of the autopilot acquisition process, the hardware was purchased, configured and connected to the vehicle’s existing systems. The existing manual control system was retained as a fallback, with the Spectre autopilot added into a parallel, alternate path. Ultimate control of the vehicle’s actuators may be switched between the legacy manual system and Spectre’s control output. Rather than being hard-wired into the vehicle, the Spectre unit itself was mounted externally on the operator’s console, with all control and sensor signals being relayed via the umbilical tether and through Wayamba’s existing network infrastructure. This greatly simplified and expedited the calibration and testing of the system as a whole.

Three weeks of trials were conducted in November 2011\(^1\) for the integration process. This included setting up the autopilot system and testing it using the AUVsim application and testing in DSTO’s water tank before spending many days conducting sea trials at Corio Quay, Geelong. This progressive sequence, from design to open-water demonstration via simulation and laboratory validation, was adopted to provide a safe and cost effective

\(^1\)Trials were conducted according to trials plan 2004/1000508/2, SI No 45/2011
development program. Very limited testing of the robustness of the Spectre autopilot’s operation when Wayamba was carrying an additional offboard system, in the form of the Murula payload [4], was also conducted. This aspect of the autopilot’s performance will be fully investigated in the future. In addition to the regular trials group members, the designer of the Spectre autopilot control system, Henry Robinson of H-Scientific UK, travelled to Australia to support the integration process.

2 Wayamba Configuration

DSTO has been developing its UUV research platform Wayamba since 1998, with an initial report detailing the design in 2002 [2]. The Wayamba platform is a 4 metre long flatfish design capable of a maximum speed of approximately 3.5 knots. Being a research platform, the vehicle’s configuration evolves over time. A companion report [3] provides a detailed description of the vehicle as it existed in mid 2010. The following paragraphs are a summary of the material included in that report.

Wayamba’s actuators consist of two main thrusters, three vertical thrusters, a single rear lateral thruster, and two bow-planes as shown in Figure 1. Large control surfaces make it very stable in flight, with the mix of propulsors yielding flexibility of manoeuvring, and the ability to hover underwater. Wayamba has two on-board computers to manage the sensors, communications, actuators and other devices, but is controlled using a remote operations system that can be set up upon a dock or support vessel. The on-board sensors include a commercial Ixsea PHINS (PHotonic Inertial Navigation System) unit, which provides an accurate estimate of the vehicle’s position when combined with a Global Positioning System (GPS) unit and a Doppler Velocity Log (DVL). Two imaging sonar devices are installed on the vehicle to provide a picture of the immediate environment around the vehicle. Communications within the vehicle and between the vehicle and operator’s station takes place through a publish-and-subscribe software architecture referred to as the WAyamba Network Environment (WANE) [5], which is summarised in Section 2.1. Both the hardware and software aspects of Wayamba have evolved to allow the rapid integration of new UUV equipment or other research payloads. Standard attachment points on the underside of the vehicle frame allow payloads to be physically integrated, while communications connection points are provided so that devices can be incorporated into the WANE network and controlled remotely via the operator’s console. This allows Wayamba to act as a concept demonstrator or “delivery truck” for both COTS and in-house technologies, such as the Murula deployment concept demonstrator [4]. One of the original aims of the integration trials was to ascertain how the Spectre autopilot would react to such augmented Wayamba configurations; however after a preliminary investigation it was decided to undertake a separate set of experiments in this area.

Wayamba is currently powered using a tether cable to a dockside (or shipboard) network and power supply. The tether provides a number of fibre optic communication lines, as well as a 3000 volt D.C. supply (converted to 350 volts on the vehicle) to cater for the various loads drawn by the thrusters and bowplane motors, computers and onboard sensors. This power supply is capable of safely providing a sustained maximum of 28 amps as measured by the thrusters, which is by default divided up to allow 2 amps for each of the vertical and lateral thrusters, and 10 amps to each of the main thrusters. Investigation
of a more dynamic allocation of the available current was undertaken during this trial to allow for a higher maximum operational speed.

When Wayamba is flown manually, the operator controls the vehicle using an Xbox style game controller with axes mapped directly to RPM commands to each thruster. A more detailed explanation of Wayamba’s manual control system is provided in Section 2.1.1. It has long been the intention for Wayamba to have a high degree of automation with a much reduced need for human intervention. One of the practical drivers for such autonomy is that it would allow the sometimes problematic and limiting tether to be removed, with power supplied instead by internal batteries. There are substantial operational challenges associated with Wayamba’s tether, such as drag forces on the vehicle and difficulties in managing loops and snags. One of the aims of the trials program was to gauge how the automatic controller would respond to forces imposed by the cable.

2.1 The WANE Software System

The WANE software was developed at DSTO to provide the communications framework for the Wayamba platform. It has evolved over the life of the project to act as an interface layer between the heterogeneous pieces of hardware that make up the vehicle and higher-level input from the operator (or a system such as the Spectre). This section of the report provides an overview of WANE focussing upon the key parts relating to the Spectre integration. For a detailed description of the WANE software and Wayamba’s WANE network, refer directly to the WANE Manual [5].

WANE refers both to a communications protocol and a set of software “nodes” exchanging messages of that protocol, forming a network. A node represents an aspect of the vehicle which may correspond to a concrete device, or something more abstract. For
example, in Wayamba there are nodes for each of the six thrusters, a node for controlling all six thrusters as a group, a node representing the altimeter unit, but also a node that publishes a single altitude estimate from the best currently available source. The nodes actively connect to a central hub and exchange messages through this hub in a publish-subscribe manner or through direct request. The Hub is responsible for keeping track of the nodes, which can enter and leave the network at any time, and distributing messages from a node to its subscribers. It does not interpret the content of the messages flowing through it or act as a central data store. This is in contrast to a system such as MOOS, where the Hub actively connects to the nodes and acts as a central mailbox for all data [6]. For WANE, data is largely passed around as-is from a source device to its subscribers, with parsing handled by the endpoint nodes as needed. The dynamic publish-subscribe system reduces the possibility that a failure in a single node might cripple the entire system, as the Hub allows any node to re-join the network at a new address. A node rejoining the network can assert itself above a crashed version of itself if need be. This dynamic nature is particularly useful when testing new nodes against the live system, as was the case with the new nodes developed for the Spectre autopilot. While the Hub represents a single point of failure, its robustness has proven to be adequate to date.

Serial communications play a major role in the WANE system, with most of the devices that make up the Wayamba vehicle operated via a serial port, including the Spectre autopilot. WANE serial nodes also have the ability to “mirror” a serial port across the network, allowing any serial port on the network to be transparently duplicated anywhere else. This was the basis for feeding serial output from the PHINS into the Spectre unit on the bench, just as if the two were directly connected with a serial cable.

The WANE network for Wayamba may be divided into two major information flows. One consists of data arising from sensors (the PHINS, DVL, sonars etc), passing through intermediary or summary nodes and then on to the user interface and operator displays such as WANE’s 3D third-person display, ThirdEye. The other consists of operator commands being routed to the thrusters and bowplanes. It is this latter flow that needed to be modified to accommodate the actuator commands from the Spectre as an alternative to the existing manual control path.

2.1.1 Manual Control

Wayamba has retained a direct manual control mode that has remained largely unchanged since its maiden voyage. The vehicle’s geometry allows a more-or-less intuitive mapping from a joystick controller to RPM commands for the six thrusters. Driving the two rear main motors at equal RPM produces forward thrust; driving one more than the other causes the vehicle to turn. The vertical thrusters may be used to attain pitch and roll or up/down motion, although controlling these can prove challenging for an inexperienced pilot. The use of a domestic Xbox controller instead of a standard joystick is a relatively recent addition, allowing control of more than one axis at once. Although this has improved the immediacy of manual control, piloting the vehicle continues to require substantial effort and concentration.

The operator interacts with a Heads Up Display (HUD) and the 3D third-person display, ThirdEye, with Figures 2 and 3 demonstrating the detail available from the 3D...
display. The HUD provides a representation of Wayamba’s pitch, roll and heading, as well as depth in relation to the water column. Running in parallel or on its own, ThirdEye depicts a 3D model of Wayamba geo-located on a chart. Scanning sonar data from the SeaKing is rendered as emanating from the vehicle model, to aid visualisation of objects in the environment relative to Wayamba. ThirdEye also depicts the DVL beams and their intersection with the sea floor as an indicator of depth and altitude. ThirdEye continues to be developed as the main interface for visualising Wayamba within the world, and has functions such as giving the distance from Wayamba to, or the absolute co-ordinates of, a user-defined point of interest. For a more detailed explanation of the HUD and ThirdEye interfaces, see the WANE manual [5].

Figure 2: A close-in view of the vehicle representation in ThirdEye

Figure 3: A zoomed-out view from ThirdEye, showing the Corio Quay chart

2.1.2 WANE Software Interface for the Spectre

Within Wayamba’s WANE network, the nodes directly responsible for actuator control are “Motr” (for the 6 thrusters) and “Bwpl” (for the port and starboard bowplanes).\(^2\) To accommodate the Spectre a pair of intermediate nodes were created to arbitrate access to these actuator nodes — respectively “Arbi” (for the motors) and “Barb” (for the bowplanes). These arbiters switch their subscriptions between the existing Xbox node emitting joystick control actions and the new node “Sptr” emitting control actions from the Spectre. In this way the arbiters act as a software cut-over switch to manual control in an emergency and consolidate management of the motors and bowplanes, without having to re-design the interface for Motr and Bwpl.

The Spectre device itself was set to output NMEA-like control sentences on the serial port connected to the new WANE node Sptr. The node translates the control sentences into a common form shared with Xbox and Sptr (and any other future control system) to be read by the arbiters. The arbiters in turn translate the control messages into the existing direct commands for the motors and bowplanes. One obvious concern arising from this design is related to latency: there may be some appreciable and unpredictable delay between the Spectre’s serial output and the eventual serial commands to the motor controllers. As will be seen later, this turned out to have little impact in practice. Figure 4

\(^2\)WANE node names always consist of 4 characters and are intended to be human-readable mnemonics.
shows an example of a control output sentence from the Spectre and its path through the WANE network and eventually to the motors.

Figure 4: The route an example control output sentence from the Spectre takes through the network to the 6 motors. Black arrows represent serial traffic; blue arrows represent network traffic.

The Spectre autopilot also relies upon vehicle status information in the form of raw telemetry from the PHINS. This was achieved with serial mirroring over the network with a stock WANE serial node. The "BinaryNav" sentences, output at 100 Hz by the PHINS, were relayed as-is to a secondary serial port of the Spectre. As this data contained critical velocity and position information the Spectre uses in its control loop, network latency and lag was again a concern.

Figure 5: High-rate PHINS navigation data was reflected as-is through the network to a generic WANE serial node local to the Spectre unit.

The PHINS maintains an internal clock with a specified stability of 50 ppm [7], synchronised to GPS time when such data is available. PHINS clock time appears in the BinaryNav sentence, which is recorded by the WANE logger with its own system timestamps. The difference between these timestamps can be analysed to estimate the lag due to the network and other factors. Figure 6 gives a representative example of lag between the recorded time in the WANE log and the time recorded by the PHINS clock (assumed ground truth). This was taken as indicative of the lag between any two nodes in the network.

The mean lag in timestamps is 5 ms, and is distributed log-normally as shown in Figure 7 below. Given that the controller updates at approximately 20 Hz, and that the
responses of the 1.5 tonne vehicle are sufficiently slow, this indicated that the combination of software routing and networking were unlikely (at least in the average case) to result in any major problems for the controller. This was indeed borne out in the trial results.

3 Autopilot System Configuration

Physically, the Spectre autopilot unit is a $12 \times 12 \times 6$ cm box having a number of serial ports as well as provisions for other analogue and digital I/O channels. These can be dynamically configured, allowing the device to be matched to a variety of vehicles with differing sensor and actuator configurations. The Spectre utilises a closed Proportional-Integral-Derivative (PID) control loop, which continuously monitors the current vehicle location and pose, adjusting the amount of actuator output required to achieve a certain control mode’s set point or desired behaviour. Where multiple control modes are applied, then the outputs to the actuators will be a combination of the commands required to reach each of the set points, allowing independent control of aspects such as heading and depth.

The autopilot may be operated with human readable NMEA messages, or H-Scientific’s proprietary compressed SSSCP protocol, which is primarily used to link the unit with H-Scientific’s software products, the Remote Control Workstation (RCW) and a simulation program AUVsim. These programs can be used together with the autopilot-in-the-loop to provide an evaluation of how the Spectre might perform before installing it on a real platform, or as an optional interface for configuration of such a platform.

The RCW software provides a graphical operator interface for setting the vehicle’s
control mode and adjusting the control set points of the vehicle using a dedicated SSSCP
serial port connection to the autopilot. This reduces the need for developers to create
their own interface before becoming familiar with the autopilot. The main RCW window
provides feedback on the orientation of the vehicle and an interface for adjusting the
autopilot’s control mode and control set points, as well as operating the automatic tuning
process. A second window provides a map based interface where the operator can define
a track using a set of waypoints and visualise the location of the vehicle. A detailed
explanation of RCW is provided in Section 3.4.

AUVsim is an underwater vehicle simulation system developed by H-Scientific, which
allows the creation of a virtual vehicle, sending simulated sensor data directly to a Spectre
autopilot. This provides a method for initial setup, tuning and testing of the autopilot
before using it on an actual vehicle. The simulator provides the ability to generate the basic
vehicle shape and add components such as fins, control surfaces and thrusters. This vehicle
configuration is used in the simulator to derive the relevant equations of motion, which are
applied to simulate the virtual vehicle’s motion. Interaction with the simulator is possible
through its own direct interface, or through the RCW software via the Spectre autopilot.
The virtual vehicle’s configuration and properties may be adjusted until it matches the
target vehicle. This process was extremely rapid; a simulated model of Wayamba, with the
control surfaces, thrusters and static features such as the sail and rear fins was generated
in less than an hour. Whilst the simulation is approximate, it provides a useful starting
point for familiarisation with the autopilot and its tuning process and it may identify if
there are potentially unstable control modes or configurations. It is important, however,
that the tuning process is run on the actual vehicle in order to provide a reliable level of
control.

Figure 7: Network lag histogram based on PHINS timestamps.
The rest of this section provides details of the autopilot’s control modes and how an operator can interact with it. Note that the software integration of the autopilot into the WANE network has been previously outlined in Section 2.1.2. Section 3.1 provides details about the range of control modes that can be used by an operator. Section 3.2 outlines the Control Allocation Module (CAM) Table which defines the basic structure of the vehicle’s actuators. Section 3.3 details the automatic tuning process that optimises the controllers based upon the CAM table and feedback from real vehicle motion, also discussing when the tuning process might need to be conducted again. Section 3.4 describes how the RCW interface provides both a visualisation of the vehicle’s current location and pose, as well as methods for the operator to interactively adjust the active control modes and their corresponding set points. Section 3.5 describes how NMEA commands can be used by an external system to send and receive commands or data directly from the autopilot via a serial connection.

3.1 Autopilot Control Modes

The autopilot offers a range of control modes: heading and speed control, depth and altitude hold, track following and the hover mode. For Wayamba, while these modes significantly reduced the workload for the operator, it should be noted that the vehicle remains reliant on direct human supervision. Pending the development of automation software, issues of cable management and obstacle avoidance still require operator intervention. Also, the autopilot does not consider issues of energy management — any future autonomous operation under battery power will require an external mission supervisor to handle all of these factors.

Each of the control modes has a set point that defines the target the autopilot will seek to maintain. The set points are accessible through the RCW interface via an SSSCP serial connection or through NMEA commands sent directly to the Spectre unit. Of the control modes, only the waypoint-based track following mode operates in a significantly different manner when using NMEA, as outlined in Section 3.1.7.

3.1.1 Heading Control

One of the most significant of the control modes is the heading control mode. This mode uses a combination of the vehicle’s actuators to turn the vehicle to the desired heading and maintain it. The mix of thrusters is adjusted, within the ability of the vehicle, to maintain that heading even in the presence of external disturbances, with the rate of turn reduced as it approaches the heading to minimise the probability of the vehicle turning past the desired heading.

As will be seen later in Table 4, the Spectre was able to maintain Wayamba at a fixed heading within a standard deviation of less than one degree over a period of some 26 minutes whilst hovering in calm conditions during sea trials. This mode also made driving the vehicle around with a combination of heading and speed control seem effortless, with the heading indicator never visibly deviating from its set point.
3.1.2 Depth and Height Control

In the Spectre autopilot, depth below sea level and height above sea floor are controlled separately from the 2D location of the vehicle. This allows for a depth or height to be maintained independently of the location based control modes, such as heading control or track following. It is also possible to change the depth or height set point at any time using NMEA or SSSCP commands from a mission control unit. A single separate command is used to change control from being based upon depth below sea level to height above sea floor. When deciding which mode to use, the physical characteristics must be taken into account, as the height above sea floor does not take account of obstacles in the area. An additional controller of the rate of change for depth is also available. This is to prevent the vehicle from ascending or descending too rapidly, which could be especially useful for manned vehicles.

During the sea trials, data from Wayamba’s Kongsberg altimeter was fed to the Spectre as a source of height feedback. While the Spectre successfully received this information, the height control mode was not tested. Depth control performed exceedingly well, both in-flight and when the vehicle was stationary. From Table 4, one standard deviation for depth hold while in hover mode amounted to about 2cm over 26 minutes. Similar results were also obtained for holding depth during track following manoeuvres.

3.1.3 Speed Control

Where information is available from the vehicle about its current speed through water or speed over ground, it is possible to engage a speed control mode to maintain that speed. When initially engaged, this mode will take the current speed as the set point to maintain; however it may then be adjusted via the RCW interface or NMEA command.

With Wayamba being a fairly low-speed vehicle with slow response times, speeds of 0.6m/s up to a maximum of about 2m/s were easily maintained when testing the speed control mode.

3.1.4 Pitch and Roll Control

For some manoeuvres it is important that the vehicle maintains a constant pitch, such as when scanning an object or area. Wayamba’s flat fish design and the limited thrust available from the front and rear vertical motors meant that the Spectre’s pitch hold mode was effective only in a constrained range. When the vehicle was stationary, the Spectre was able to attain and maintain reasonable pitch control. However, when in motion, the controller would run into the physical constraints of the system and struggle to maintain a set pitch that was significantly different from the vehicle’s natural pitch. Especially when moving forward and changing depth, it was found that the controller had difficulty maintaining a pitch of zero at any significant speed.

Operating similarly, roll control may be used to maintain the vehicle in a stable flat condition throughout manoeuvres, minimising any potential disturbance to sensors such as sonar devices. This may be especially useful where vehicles have a natural tendency to
roll during turns. For Wayamba, the Spectre could maintain roll control more successfully than pitch control.

3.1.5 X and Y Directional Control

In the Spectre’s reference frame, positive X points forward, positive Y points starboard, and positive Z is down. Once tuned, the X-Y control mode will allow the autopilot to move the vehicle at a given percentage of the vehicle’s capacity in the X or Y directions. While most underwater or surface vehicles are capable of travelling forward or reversing without having to turn, the X direction, few are capable of travelling port or starboard, the Y direction, without also travelling in the X direction. Wayamba’s combination of thrusters does allow for it to move in the X and Y directions independently, if very slowly, allowing for these control modes. This motion is important for station keeping in the hover mode, but could potentially be used for positioning a vehicle for recovery after a mission is completed. This control will not operate sensibly without appropriate tuning.

3.1.6 Hover Control

The hover control functionality is a constituent of Dynamic Positioning (DP) control, which has the following four modes:

1. DP0 (Dynamic Position 0), where the operator chooses hover-position as a north, east reference point.

2. DPH (Dynamic Position with heading), as with DP0, but with the operator also specifying a heading to maintain.

3. ADP0, as with DP0, but the position is specified in terms of an area, defined by a position and radius.

4. ADPH, area hover as with ADP0, with a specified heading.

The operation of these DP modes requires an automatic tuning process to be performed for the X and Y position controllers and the heading controller. This automatic tuning process is generally only required to be performed once with the setting saved into the Spectre’s memory and reloaded during subsequent run time. The process of automatic tuning the Spectre is outlined in Section 3.3. Once tuned, the vehicle can be set to any of the four DP modes via the RCW interface or via direct NMEA command messages. Of the four modes, the area DP modes, ADPH and ADP0 provide the greatest efficiencies, by allowing the vehicle to respond to drift at a slower rate. This sensitivity to drift is adjustable by setting the Stability Coefficient for each of these two modes. In terms of energy consumption, the area mode ADP0 offers the greatest hover efficiency by allowing the controllers to calculate the most efficient heading to put the vehicle onto. The most effective heading for Wayamba is the one that opposes the currents acting on the vehicle, as determined from its sensor readings, as it can utilise the main thrusters to oppose the current and it presents the smallest frontal surface area to that current.
The hover controller uses the PHINS positional information to observe the drift of the vehicle and engage the vehicle’s thrusters to maintain the desired position. It should be noted that the hover control is only concerned with the position of the vehicle in the horizontal (X, Y) plane, although depth control may be engaged independently. In Wayamba’s case the controller actuated a combination of the two main rear thrusters and the lateral thruster to maintain position and heading, at times well within the positional accuracy of the PHINS, as detailed in Section 4.3. Of the four control modes, it was also found that only the DPH mode should be used as allowing the Wayamba to find its own heading, and to move around within a given area, could lead to the tether cable becoming entangled.

3.1.7 Track Following

Enabling a vehicle to follow a path between a set of waypoints, or following a track, is often a crucial component of a mission for an AUV. The RCW has an interface for creating an ordered set of waypoints using mouse clicks upon a geo-referenced map to generate a track. Once entered, waypoints can be reordered and adjusted, with a popup even allowing for a more accurate location to be entered. An example of this RCW interface is shown in Figure 8 in Section 3.4. The operator can also define the vehicle’s behaviour upon completion of the track, which could include repeating the track, continuing on the same heading, or hovering in place. Tracks created in this manner exist locally within RCW and are then uploaded to the Spectre autopilot in their entirety before commencing the track. When the track following mode is enabled, the autopilot will begin manoeuvres to reach the first waypoint. Once the waypoint is reached, it will continue following subsequent waypoints until the track is completed. The autopilot determines that the waypoint has been reached when the vehicle has crossed a line perpendicular to the current track leg at a distance equal to the watch distance. If the turn to the next track leg at the current speed is greater than the watch distance, then the waypoint is deemed to be reached earlier allowing for more time to conduct the turn. The criteria for reaching waypoints whilst in track following mode is covered in more detail in Section 4.2, where the results outline the autopilot’s advantages and limitations. The autopilot has been recently adapted to ensure its heading is within 90 degrees of the bearing to the current waypoint, to restrict the possibility that a tethered vehicle like Wayamba might turn in the wrong direction and potentially entangle the tether cable. Operator care is required to ensure the track is achievable by the vehicle being controlled by the autopilot in the operational conditions. When no track has been uploaded, the autopilot will use the last track that was uploaded.

3.2 The Control Allocation Module Table

For the Spectre autopilot to effectively control the vehicle’s motion, it requires a model of the vehicle which defines how the operation of each actuator will affect the vehicle’s motion. The Spectre uses a Control Allocation Module (CAM) table to link each actuator with a machinery number and to define the effect of that actuator on the vehicle’s position and orientation. Typically, a value of +1, 0, or -1 is entered into the table with the sign indicating the direction and a zero indicating no effect. These act as a starting point for the vehicle model. A separate scaling coefficient affects the resolution of the PID controllers.
If during testing the PID coefficients are found to be at the extremes of the range, scaling should be used in the control allocation module itself. The autopilot’s CAM table allows for a maximum of 12 actuators. Table 1 shows the CAM table developed for Wayamba.

Table 1: The Control Allocation Module Table for Wayamba

<table>
<thead>
<tr>
<th>Actuator</th>
<th>Output No.</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>Roll</th>
<th>Pitch</th>
<th>Yaw</th>
</tr>
</thead>
<tbody>
<tr>
<td>Port Main</td>
<td>0</td>
<td>1.0</td>
<td>0.3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.0</td>
</tr>
<tr>
<td>Stbd Main</td>
<td>1</td>
<td>1.0</td>
<td>-0.3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-1.0</td>
</tr>
<tr>
<td>Front Vertical</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>-1.0</td>
<td>0</td>
<td>1.0</td>
<td>0</td>
</tr>
<tr>
<td>Port Vertical</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>1.0</td>
<td>1.0</td>
<td>-1.0</td>
<td>0</td>
</tr>
<tr>
<td>Stbd Vertical</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>1.0</td>
<td>-1.0</td>
<td>-1.0</td>
<td>0</td>
</tr>
<tr>
<td>Lateral Thruster</td>
<td>5</td>
<td>0</td>
<td>1.0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-1.0</td>
</tr>
<tr>
<td>Port Bowplane</td>
<td>6</td>
<td>0</td>
<td>0</td>
<td>1.0</td>
<td>-1.0</td>
<td>-1.0</td>
<td>0</td>
</tr>
<tr>
<td>Stbd Bowplane</td>
<td>7</td>
<td>0</td>
<td>0</td>
<td>1.0</td>
<td>1.0</td>
<td>-1.0</td>
<td>0</td>
</tr>
</tbody>
</table>

In Wayamba’s case it can be seen that the actuators influence more than one degree of freedom. Scaling has been used on the port and starboard main thrusters to account for the small effect they have in the lateral (Y) motion of the vehicle, allowing them to be used to compensate for the yaw effect of the rear lateral thruster when maintaining control in the Y direction. Once the CAM table has been determined, the Spectre autopilot utilises an automatic tuning process to optimise the control coefficients.

3.3 Automatic Tuning Process

Of Spectre’s eight control modes, seven have automatic tuning algorithms to determine coefficients for the PID controllers. The seven modes are listed below and the automatic tune process should be performed in the listed order:

1. heading
2. roll
3. pitch
4. depth or height
5. hover X
6. hover Y
7. speed

Before commencing any automatic tuning process, the vehicle’s buoyancy should be made as neutral and balanced as possible. If the buoyancy is not neutral, the actuators that affect the vehicle motion along the Z axis will be operating continually in order to maintain the set depth or height. Their effect on this axis will also vary depending upon whether the vehicle is submerged or at the water’s surface. For each actuator, the controller’s output
range is +100% to -100% and any imbalance in the vehicle’s buoyancy creates an offset in the controller’s effective range. For example, if the vehicle was positively buoyant and the controller was required to devote -30% of an actuators output to depth maintenance, this would leave the controller with the remaining -70% for additional manoeuvres. This would limit the vehicle’s capabilities and be very inefficient in terms of energy use.

Another area that may affect the success of the tuning process is free play and hysteresis in the mechanisms of any control surfaces. Mechanical free play and hysteresis causes vehicle instability as the controller tries to constantly correct for unexpected results. Below is an overview of areas where failure to undertake adequate preparation work can adversely impact the auto tune process and ultimately the controller’s effectiveness:

- Buoyancy should be as neutral and balanced as possible;
- Ensure there is minimum free play in mechanical control systems, to reduce hysteresis;
- Fixed control surfaces should be adjusted so that the vehicle does not pitch or roll during straight forward motion at operating speed;
- The system should be tested for latencies, which should be reduced where possible.

The automatic tuning process can be initiated once the Control Allocation Module is populated and checked for correct operation. The tuning process can be performed via the RCW interface or using direct NMEA or SSSCP commands. The RCW interface is covered in more detail in Section 3.4. For Wayamba’s heading control, the tuning process consisted of the Spectre making small oscillations in heading, determining the response of the vehicle to the actuators. The automatic tuning of other modes involved similar small oscillations about the axis of control. On completion of the manoeuvres the controller coefficients are set and may be adjusted manually if necessary. Unless the vehicle undergoes a significant alteration to its hydrodynamic form, or undergoes modification to its configuration of thrusters or control surfaces, it is usually not required to undergo the tuning process again.

It is worth noting that the tuning process may be conducted with a virtual vehicle in H-Scientific’s AUVSim software. This is particularly useful for new vehicle designs or configurations which have not been tested in the water before, as the simulator can provide an approximation of the system performance. It is important to remember that such simulations are approximate and that the tuning process should be conducted carefully on the real vehicle before it can be used with any confidence. This software was demonstrated to DSTO personnel during the trial, where its performance seemed a reasonable match for Wayamba’s movement characteristics; however it was not possible to undertake a systematic evaluation as the software was provided by H-Scientific as demonstration software only.

## 3.4 Operating the Autopilot using the RCW

The RCW provides the operator with an easy interface for achieving vehicle control using a dedicated serial port connection to the autopilot. The autopilot’s physical connections
are set up using the configuration port and a small configuration program. This program allows the user to define which of the autopilot’s connections are dedicated to the protocols required for key tasks, such as which serial ports are providing SSSCP or NMEA interfaces, or defining any digital or analogue connections to the autopilot. Figure 8 shows a typical RCW display, which repeats standard sensor feedback to the operator. This feedback is also available in the WANE interfaces described in Section 2.1, though the RCW map only provides a 2D representation of location. In addition to the sensor feedback, RCW also provides an indicator to show that the connection to the autopilot is active, buttons to set the control modes of the autopilot and indicators of the current control set points for each active mode. Drop down menus are also provided to allow for customisation and access to configuration parameters. The set point is initialised as the current value when the control mode is enabled to minimise any disturbance to the platform. These set points can be changed by clicking and dragging on the interface, which then sends the revised command to the autopilot. These commands are sent using SSSCP, with the changes in RCW not being finalised until an acknowledgment is received from the autopilot. The set point will snap back to the current value if the update fails. RCW also provides an interface to run the autotune process for the current control mode. The interface is designed to be customisable, with the option for a user to adjust the location of any of the displays or controllers, as well as adding or removing controllers as desired.

![Figure 8: The RCW user interface to control the autopilot](image)

The second component of the RCW, shown on the right of Figure 8, shows a map display of the current location of the vehicle which the autopilot is controlling. This display can be provided on a background of a geolocated image of the area, though accurate alignment can be difficult. This map interface allows for a user to insert waypoints into a track by selecting where they should be positioned. Additional waypoints can be inserted into the track, or an existing waypoint can be selected and adjusted as required. If the entire track is selected, then the track can also be quickly moved, rotated or scaled. Once the track has been generated, it can be transferred up to the autopilot, which may take a few seconds. When the track is successfully uploaded, the operator can enter track following mode for the vehicle to begin following the track. The operator can also specify which behaviour occurs after the track is completed, including whether the vehicle repeats the track, continues on the same heading, or enters hover mode once the track is completed.
3.5 Operating the Autopilot using SSSCP or NMEA Commands

One alternative to using RCW to control a vehicle like Wayamba is to directly send NMEA commands or the proprietary SSSCP commands to the Spectre autopilot. These messages can achieve similar behaviour to using the RCW directly when they are integrated into the system software as they inform the autopilot about the desired manoeuvring controls. The commands are sent using a software library of SSSCP functions that can be purchased separately to the autopilot, or as human readable NMEA text commands. Both message formats operate in similar manner, except for developing waypoints and following a track. The integration of these commands into the software of the vehicle allows the system developers to have greater control over the autopilot’s operation and can allow the system to autonomously make decisions about the execution of the current mission, such as adjusting to the local environment or prioritising tasks, with the autopilot focusing upon achieving the actuator behaviour for the local vehicle motion. Developers of the mission module will need to carefully consider the level of human interactivity that is required to adapt the existing mission, as communications may be limited, especially where underwater vehicles do not have a communications tether.

The Spectre Autopilot user manual explains each of the NMEA commands the unit emits or recognises, the relevant commands for Wayamba are summarised in Table 3.5 below. These commands include the APM command, which can be used to switch between the control modes outlined in Section 3.1. Each mode has a corresponding command to provide the relevant control set point, such as the DTH command for Depth. The autopilot also accepts COP and NVO commands to determine which serial ports to send data feedback from the autopilot. The COP command tells the autopilot which serial port will provide feedback about the vehicle’s actuators, which can be individually included or excluded. Once the COP command has been sent, the autopilot will then send MCO commands, which provide the autopilot’s desired value applied to each actuator the system controls in the range of -1 to 1. The NVO command determines the serial port and rate at which the autopilot will provide information about the vehicle’s depth and orientation. Note that the autopilot does not repeat a location estimate of the vehicle.

The autopilot can run the automatic tuning process using the ATC command. This command determines the mode to be tuned, and provides the parameters defining the amplitude of manoeuvres to perform and a time by which the tuning should be completed. An acknowledgment is sent upon the successful completion of the process confirming that the control parameters have been updated. Using this command it is possible to develop an automated program that could loop through each of the control states to perform a fully automatic tuning of the vehicle without operator intervention.

The only mode which operates differently depending upon whether SSSCP or NMEA commands are used is the track following system. The assumption of the Spectre developers is that developers using NMEA commands would use their own track following algorithm. Thus the Spectre does not provide any acknowledgment of reaching a waypoint, or allow a method to input waypoints using NMEA commands. The capacity for an external track following algorithm may be realised through the use of the cross track error and bearing NMEA command XTB. This command has a measurement in meters of the distance of the vehicle starboard from the current track leg and the bearing to the end
Table 2: NMEA Commands used to send and receive data from Spectre

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Command</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADP</td>
<td>Depth/Height Attitude mode</td>
<td>Enables or disables the control modes for Depth/Height, Pitch and Roll.</td>
</tr>
<tr>
<td>APM</td>
<td>Autopilot mode</td>
<td>Switches the current control mode of the autopilot.</td>
</tr>
<tr>
<td>APT</td>
<td>thrust mode</td>
<td>The speed set point in Knots.</td>
</tr>
<tr>
<td>ATC</td>
<td>Autotune Command</td>
<td>Activates the automatic tuning operation for the current control mode using the parameters provided in the command.</td>
</tr>
<tr>
<td>CFN</td>
<td>Configure Nav output</td>
<td>Defines the output interval of position data</td>
</tr>
<tr>
<td>COP</td>
<td>Command output</td>
<td>Defines which port to output motor control commands.</td>
</tr>
<tr>
<td>DHA</td>
<td>Depth, Height, Attitude output</td>
<td>Outputs the depth, height, roll and pitch sensor data.</td>
</tr>
<tr>
<td>DTH</td>
<td>Depth set point</td>
<td>Defines the depth set point and max rate of depth change.</td>
</tr>
<tr>
<td>HTH</td>
<td>Height Set point</td>
<td>Defines the height set point above sea floor</td>
</tr>
<tr>
<td>HVP</td>
<td>Hover point</td>
<td>Sets the X and Y location of hover position</td>
</tr>
<tr>
<td>MCO</td>
<td>Motor Control Output</td>
<td>A string which defines the commanded percentage of output that should be applied to each actuator.</td>
</tr>
<tr>
<td>NVO</td>
<td>Navigation Vehicle Output</td>
<td>Defines the port and output rate at which the autopilot will output vehicle data in the form of X commands.</td>
</tr>
<tr>
<td>THD</td>
<td>Thrust Demands</td>
<td>Direct CAM demands for motion control</td>
</tr>
<tr>
<td>VBW</td>
<td>Ground and Water Speed</td>
<td>Output of the Ground and Water Speed</td>
</tr>
<tr>
<td>XTB</td>
<td>Cross Track Error and Leg Bearing</td>
<td>Defines the vehicle’s current cross track error, or distance starboard of the current track leg, and the leg bearing. The autopilot minimises cross track error whilst achieving the desired bearing.</td>
</tr>
</tbody>
</table>

of the track leg. Upon acknowledging receipt of this command, the autopilot will perform manoeuvres to minimise the cross track error, or distance from the current track leg, and to reach the desired bearing. The external track following system would send adjusted XTB commands to the Spectre as waypoints are reached or other conditions arise. The advantage of this approach is that obstacle avoidance can be achieved dynamically by using a set of XTB commands to direct the vehicle around the obstacle. Normally this would require an operator to exit track mode and take manual control through the RCW. During the November trials, driving the Spectre with XTB commands was not tested due to time constraints.
4 Performance Validation Trials

The trials being reported were conducted in accordance with trial plan 2004/1000598/2, SI No 45/2011 during November 2011. These trials investigated the integration of a Spectre autopilot unit into the control system for Wayamba and how it can be effectively used to achieve accurate control. The results presented here use a combination of evaluating feedback from the Wayamba operators and an analysis of the data logs obtained of Wayamba’s actual and expected motion. Four operators were involved in the use and evaluation of the Wayamba system with the autopilot integrated, including one experienced Wayamba pilot, two operators who were familiar with the existing operator interface, but had limited experience in operating it and one operator who had no experience in operating Wayamba.

The trials were performed in a number of stages to assess the performance of the autopilot. As the trials progressed, the assessment became more operational in nature; that is, they explored how effectively the autopilot could control Wayamba in operationally realistic situations.

The first stage of the trials was used to investigate the potential of the autopilot to operate with a simulated Wayamba and to familiarise operators with the control interface. The second stage involved a set of trials within DSTO’s water tank to verify the integration of the system to allow the autopilot to control Wayamba’s actuators and to verify the autopilot’s automatic tuning process as far as possible. The third stage involved sea trials of the Wayamba vehicle in Corio Quay to investigate the autopilot performance in a more open sea environment.

The results section begins by examining the usage of the RCW to control Wayamba through each of the three stages. This evaluates the operators’ experience with the use of the RCW to control Wayamba and compares the performance difference when the vehicle is operated using the existing manual control method and using the autopilot assisted control. It also describes the problems that occurred when integrating an X-Box style controller directly into RCW. Section 4.2 examines the ability of the autopilot system to perform track following by analysing key performance indicators such as the cross track error, and the system’s ability to perform the required manoeuvres. Section 4.3 analyses Wayamba’s performance when it enters the hover mode, identifying limitations in this mode that might affect mission planning.

4.1 Direct Control of Wayamba Using RCW

The proprietary RCW software interface was developed by H-Scientific as a specific interface through which an operator can control a vehicle fitted with their autopilot using its compact SSSCP commands. The RCW provides a graphical user interface through which commands are then sent directly to the Spectre autopilot through a dedicated serial port. The autopilot relies upon data about the vehicle’s location, orientation and other data from an external source, which it then controls using actuator commands to achieve the desired vehicle control. Thus a combination of the autopilot and a source of vehicle data, either from Wayamba’s PHINS unit, or simulated data from AUVsim are required to evaluate the use of RCW to control Wayamba.
4.1.1 Simulation Trials

A simulated physical model of Wayamba was created in AUvSim through the generation of the main body and attaching fins, bowplanes, and thrusters at the appropriate locations based upon the plan view of Wayamba, given as Figure 9. This model was used by AUvSim to estimate the equations of motion which describe how its Wayamba model should move through the water to mimic the real vehicle’s motion. Whilst this method only provides an approximation of Wayamba’s expected motion, it was used to verify that the configuration of the autopilot reflects the physical structure of Wayamba. This process also ensured that the autopilot provided commands that appeared to control the Wayamba model appropriately. Although a detailed comparison of the motion of the model and real vehicle motion data were not conducted due to time restrictions (the reader is reminded that AUvSim was provided by H-Scientific for the purposes of limited evaluation only), the operators did note that the modelled motion appeared similar to their experience of Wayamba’s motion. It is important to note that the simulator motion does not attempt to model surface effects that might influence the vehicle, so interactions at the surface are not realistic.

The simulation stage of operating the autopilot allowed the operators to become familiar with the RCW interface and the control modes that were now provided. One significant change noted by all the operators was the lower level of interaction that is required to operate the vehicle. Using the existing manual interface, all of Wayamba’s actuators will be inactive unless the operator is directing them to be active with the controller. Within the RCW it is possible to use control modes at a given set point and leave the vehicle moving in a prescribed way without physically interacting with RCW. This reduces the physical activity of the operator and may reduce the risk of some health problems, such as occupational overuse syndrome, as the operator is mostly observing the vehicle and only changing the control mode or set point when a change in vehicle behaviour is required. It was also noted that maintaining a constant setting on a vehicle parameter, such as heading, required little effort when using the RCW as this corresponds to autopilot control mode set points.

The tuning process was also conducted in the simulated environment to gain operator familiarity and determine approximate parameters that could be used when tuning the physical system. This was useful as the ability to tune the vehicle is determined by the time allowed to perform the tuning process for each control mode, and the level of actuation around the control mode’s set point. Whilst AUvSim only provides an approximate model, it provides an indication of whether the tuning time or the level of actuation around the control mode’s set point might be too small to be effective, potentially reducing the time a vehicle may require in the water to successfully complete the tuning process. It was determined in this process that the tuning of depth control and the Y directional control may require longer than the standard 20 seconds to complete as they were not completed successfully in the simulation. This simulated tuning also provides a starting point for the tuning process, though performing the automated tuning upon the physical vehicle is crucial to achieve effective autopilot control. When tuning Wayamba in the open ocean, the standard 20 seconds time was used successfully for all automatic tuning manoeuvres, except for the Y directional control, which required a 40 second tuning window.
Figure 9: Plan view of Wayamba
4.1.2 DSTO Indoor Tank Trials

The second stage of the trial involved connecting the RCW to the autopilot and using the data from Wayamba’s PHINS unit as the feedback of physical system data. This was achieved with Wayamba in the DSTO fresh water test tank to provide a feedback of real system data. This stage verified that the RCW could send commands to the autopilot system through the internal WANE system to operate Wayamba in the same manner as its simulated form in AUVsim. It also confirmed that the RCW display received and accurately reflected Wayamba’s position and orientation during its limited manoeuvring. The freshwater tank trials also confirmed the operation of several of the control modes with the exception of height above sea floor, speed control and track following as the size of the tank was too small to allow significant manoeuvring. These tests also highlighted the fact that the autopilot is relying solely upon vehicle pose data, so operators need to take care to avoid situations where Wayamba may collide with another object, or snag its tether cable.

4.1.3 Sea Trials

The third stage of sea trials were conducted over 5 days at the Corio Quay in Geelong. These sea trial days provided an open water environment with which to investigate the full range of the autopilot’s control modes. Whilst the operators initially piloted Wayamba at or near the ocean surface so the vehicle could be tracked visually, the confidence in the autopilot system and the feedback provided by both RCW and ThirdEye grew to the point where Wayamba was generally operated at a depth of 2 metres or more, where the vehicle is no longer visible from the surface. The operators used the RCW interface for vehicle control, but still relied heavily upon the ThirdEye’s 3D display as this provided the sonar data relative to Wayamba, which indicated underwater objects and obstacles. The features of the WANE HUD is largely replicated in the RCW to provide feedback on Wayamba’s pitch, roll, yaw and depth. The redundancy of these data resulted in less experienced operators relying mainly upon the RCW interface, except when they wished to observe the sonar data. The operators suggested this was because it was easier to observe the current vehicle parameters and the control set points this way. The most experienced operator tended to focus mainly on the existing WANE HUD and ThirdEye interface to ensure that any changes in the sonar readings were observed early, and only use RCW when actively changing control set points or control modes. The flashing depth indicator used in the existing WANE HUD to show when Wayamba neared the bottom of the quay was a key difference between the HUD and RCW, which provided a more noticeable sign that the operator should intervene when nearing the bottom.

During the sea trials it was noted by the operators that it is much easier to maintain a constant set point on a given vehicle parameter using the autopilot. To evaluate this, the most experienced Wayamba operator compared the difficulty of maintaining a constant heading over a period of a more than minute using both manual and autopilot control. The results shown in Figure 10 show the manual path and its heading variation on the left, which is compared to an autopilot controlled path on the right. During the manual control period, the operator was asked to make a turn onto a new heading and then attempt to maintain the new heading for approximately 50 metres, which lasted approximately 60
seconds. The heading varied by up to 20 degrees during this period, with gradual shift over the experiment as can be seen on the left side of Figure 10. A comparative section of automatic control was also conducted over approximately 190m, which lasted over 150 seconds, with a heading variation of less than one degree. This confirms observations that were made during all stages of the trial, indicating that the autopilot provided more accurate control of vehicle parameters with significantly less effort than using manual control.

To analyse the performance of the Spectre autopilot data logs of RCW were collected along with the WANE logs for the trial. These RCW data logs are provided as a set of Matlab readable data files with an array for each variable that was logged. These data are separated into categories of which three are of interest. Data prefixed by NAVAIDS is obtained by the autopilot directly from the vehicle, primarily from the PHINS unit. Ctrl_Sys is the prefix for data about control variables within the Spectre unit, whilst SPX_MCD is the prefix for motor control demands that were sent from Spectre to Wayamba’s actuators. The data can be plotted to show any values of interest, such as the X and Y positions, velocity, heading, depth, thruster commands and other vehicle data, such as pitch and roll, over a given time period.

Figure 11 shows a section of an RCW log that is approximately 7 minutes long, with Figure 12 displaying the vehicle data obtained over the same period. This combination of plots show that Wayamba started initially from a low velocity before accelerating to its highest speed, whilst diving to 3 metres at the same time. It then began to slow down and turn to starboard before moving back towards its initial position. During the highest speed component the vertical thrusters were not activated, allowing for more power to be available to the main rear thrusters, with only one period of significant roll recorded whilst turning to starboard. The data can also be further analysed to identify the operator behaviour during the manoeuvre. For instance it is clear that the operator adjusted the heading point multiple times whilst cornering to ensure that the vehicle turned the correct direction to achieve the desired heading. This manoeuvre was done to ensure that Wayamba did not create any tangles in its tether cable.

The use of RCW to control Wayamba also allows for a more accurate investigation of the effect of changes to vehicle configuration to the vehicle’s key parameters. This can be achieved by using a more repeatable pattern of manoeuvres to provide results about vehicle parameters, such as the speed at a percentage of maximum vehicle thrust. Future trials will be used to determine the most appropriate manoeuvres for this evaluation. During the sea trials a comparison of speed under three configurations was performed, with the results given in Table 3. The configurations compared included the standard Wayamba configuration where a tubular steel frame surrounds forward bowplanes as shown in Figure 9 above. This frame protects the bowplanes from collisions and are often referred to as bumpers; however they were also considered to create drag, which reduce the speed of Wayamba and the effectiveness of the bowplanes. A second configuration was therefore tested by removing the bumpers from around the bowplanes. A third configuration was also tested by increasing the maximum current of the main thrusters from 10 Amps each to 14 Amps each. This increase in power could normally overload the power supply if the manoeuvring thrusters were used, so they were disabled for this test. Whilst this mode allowed for the fastest speed, it had the consequence of reducing Wayamba’s manoeuvring capability. While Table 3 clearly demonstrates that improvements to the hydrodynamic form
**Figure 10:** Comparison of Manual (left) and Automatic Heading Control
Figure 11: Example of Wayamba operating at high speed
Figure 12: Example of Wayamba operating at high speed
and increasing propulsive power both resulted in increased maximum speeds, non-linear effects such as drag would ultimately limit the gain that could be achieved. Considerations of speed and power requirements will be an important component of an effective mission management system and will require future investigation. It should also be noted that if the bowplanes are left unprotected, then greater care must be taken to avoid collisions which could potentially damage them. A similar procedure could be used to investigate the impact of other configuration changes, such as mounting the Murula deployment system [4], where the impacts upon the vehicle dynamics are going to be more significant.

Table 3: Speed in m/s at a given percentage of maximum thrust for 3 configurations

<table>
<thead>
<tr>
<th>Forward thrust (%)</th>
<th>Normal</th>
<th>Bumpers removed</th>
<th>Extra power</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 %</td>
<td>0.51</td>
<td>0.61</td>
<td>0.7</td>
</tr>
<tr>
<td>60 %</td>
<td>0.81</td>
<td>0.87</td>
<td>1.2</td>
</tr>
<tr>
<td>80 %</td>
<td>1.09</td>
<td>1.15</td>
<td>1.54</td>
</tr>
<tr>
<td>100 %</td>
<td>1.30</td>
<td>1.45</td>
<td>1.97</td>
</tr>
</tbody>
</table>

4.2 Track Following Control

A key advantage of having a vehicle with an autopilot is having the capability for the vehicle to accurately conduct a series of complex manoeuvres without requiring operator intervention. A typical example of such an activity for an AUV might be scanning an area to find potential underwater mines. The Spectre autopilot system provides a track following mode to allow operators to program this task through the RCW interface as outlined in Section 3.1.7. The underlying assumption of the autopilot’s track following mode is that the map locations of the vehicle will be controlled separately to the other vehicle parameters, such as speed and depth, so the waypoints in the autopilot system are only stored in two dimensions. The software developers of the autopilot noted that this could be adjusted if it was required; however in their experience most operators prefer to set the other vehicle parameters such as depth and speed before running the track in an autonomous manner. Indeed, when operating in unfamiliar waters, some operators check for hazards by electing to undertake a preliminary survey in which the vehicle follows the track while remaining close to the surface.

The track following mode was only tested using the RCW interface during this set of trials, as the infrastructure for a mission control module using NMEA commands has not yet been implemented for Wayamba. As explained in Section 3.1.7, waypoints for the track are entered by clicking on the desired location in the area map window, with waypoints being connected in the order they are entered to generate the track. Figure 13 shows an example of a track entered in RCW which was followed by Wayamba at Corio Quay. The yellow, labelled triangles indicate the location of waypoints, with the green connecting lines showing the track legs between the waypoints. The white line indicates Wayamba’s movement as it followed the track, as determined by the inertial navigation system, with the triangles providing periodic indications of Wayamba’s orientation at that location. It can be seen that Wayamba accurately followed this track, though the turns at the end

\[^3\]Typically descriptively and colloquially called “mowing the lawn” in the mine countermeasures domain.
of each straight section were constructed to ensure that Wayamba could easily make the turn. A Pop-up window can be obtained by double clicking points to allow the user to rearrange the order of waypoints, or enter a more exact location for a given waypoints if desired.

![Figure 13: Example of RCW interface showing Wayamba following a track](image)

### 4.2.1 Simulation Trials

The track following mode was used during the first stage of simulated Wayamba motion to gain familiarity with its operation. During this stage the operators found that whilst it is easy to generate a set of approximate positions for the waypoints that form a track for a vehicle to follow, it can be difficult to get the precision of individual waypoints to under a metre. Such accuracy is likely to be acceptable for most cases, as the effects of currents and tides will have a significant impact upon the vehicle’s ability to maintain the correct path. Where accuracy is required, such as maintaining an overlap when scanning to find underwater mines, care should be taken by the operator to ensure the path is achievable and includes enough robustness and overlapping regions to achieve the desired mission goals, such as area coverage. The motion of the simulated Wayamba appeared consistent with the operator’s experience of the actual vehicle’s motion, except that it does not simulate the power and communications tether. This tether limits the manoeuvres that can be performed without becoming entangled or snagged.
4.2.2 Sea Trials

The size of the DSTO freshwater tank did not allow for the control modes used for track following to be tuned or tested during the second phase of the trials, so this time was used to prepare for the open sea trials. Tracks were developed in RCW based upon the simulated experience, with the first track developed to have curves for Wayamba to turn between a series of straight segments approximately 10 metres apart. In its initial configuration Wayamba’s speed was set to approximately 0.6 m/s.

The first application of the track following mode to operate Wayamba in a mine search style pattern uncovered some limitations of the autopilot and a concern with the way the autopilot determined that the waypoint had been reached. The most important limitation of the autopilot is that it is not aware of the tether cable which provides Wayamba’s power and communications. Thus when executing a turn, the operator must be careful to ensure Wayamba will turn in the correct direction and not twist or entangle the tether. Using the RCW interface, the operator can achieve this using a series of smaller turns to rotate in the correct direction, as the autopilot attempts to turn in the direction that requires the least rotation. This consideration is also crucial when planning a track for Wayamba to follow automatically, with careful placement of multiple waypoints to ensure the correct rotation direction, and to ensure that the speed is not too high for the expected manoeuvres. A number of manoeuvring options available when the track is completed can potentially lead to tether entanglements, so we would recommend an operator or sophisticated control system takes control, or maintains oversight, of the vehicle at this stage.

The autopilot determines that the vehicle has reached a waypoint based upon the distance to the waypoint, the rotation required to reach the next leg of the track and the operator defined distance at which a waypoint is reached, called the watch distance, as outlined in Figure 14. The autopilot initially calculates a line perpendicular to the current track leg at the watch distance away from the current waypoint. When the vehicle crosses this line, it has reached the waypoint. Where a significant rotation is required to steer onto the next track leg, the autopilot shifts the line further along the track to allow the vehicle more time to execute the turn, as shown for the top left waypoint in Figure 14. This extension of the distance at which the waypoint is reached caused a problem for operating Wayamba with close-spaced parallel tracks, as waypoints were deemed to have been reached because a large rotation was required, or the next waypoint is too close to the current waypoint. Wayamba thus unexpectedly reached a series of waypoints, according to the logic built into the autopilot, and rotated in the wrong direction, which could have entangled the cable if the operator had not intervened. An additional requirement has been added such that a waypoint is only reached when the vehicle’s heading is pointing towards the waypoint (within ±45 degrees). This reduces the possibility of Wayamba rotating in an unexpected direction when following a track. Care is required by the operator to ensure that the track is undertaken at an appropriate speed, with a larger turning radius used when operating at higher speeds and a series of waypoints used to approximate curves or ensure the correct turning direction. It is also important to construct the track to ensure the vehicle reaches its goals, which might include having waypoints past the point of interest to ensure the vehicle does not turn too early to make the next track leg. A higher level of control and flexibility can be gained using a customised track following system implemented using the autopilot’s messaging interfaces whilst still using the autopilot’s
other control modes, which may be further investigated as a part of Wayamba’s mission management system.

Figure 14: Determining when a waypoint is reached in the autopilot

The track following mode was analysed using results derived from the tracks depicted in Figure 15 and Figure 18 below. Figure 15 shows the track following that was conducted from the south wharf at Corio under the standard Wayamba configuration shown in Figure 9. The track consisted of a series of 3 straight segments with turns to ensure that the tether was not entangled. At the end of the 3rd straight segment Wayamba was programmed to follow an approximately curving segment before completing the track. Because of its starting position and orientation, Wayamba had to turn 90 degrees to port to reach the start of the track. The waypoints for this track are shown as green triangles, with the green line indicating the track leg between the waypoints. The blue line shows the position of the vehicle as determined by the inertial navigation system, with red circles placed every 30 seconds to give an indication of Wayamba’s speed through the water.

Figure 16 shows the data collected from the vehicle whilst following this track. The forward velocity of Wayamba closely follows the velocity set point, though it varies slightly during the sharper turns at the end of the straight segments. The heading control shows a small amount of overshoot, though it does accurately follow the heading set point. The heading graph also shows that the heading is adjusted by the controller in a series of small steps to achieve the final long curve. The depth graph demonstrates that Wayamba is capable of accurately maintaining a depth of 3 metres (outside the surface effects at Corio Quay) throughout the entire track, though the thruster demands indicate that Wayamba was not trimmed to drive completely level. The results show that the front vertical thruster is working to push the nose up, whilst the rear verticals are pushing the rear down, with the graph of pitch indicating a natural pitch of approximately 2 degrees down. The port vertical thruster is operating more strongly than the starboard vertical thruster indicating
that Wayamba has a slight tendency to roll to the port side, which is confirmed with a slight variation in the graph of Wayamba’s roll.

One measure of how well a vehicle is able to follow a track may be attained by analysing the cross track error, or perpendicular distance from the current track leg.\textsuperscript{4} This is important to ensure a vehicle is covering the designated area effectively when searching for objects such as mines along the straight track segments. Obtaining data from track following along long straight sections was not a priority of this trial; however Figure 17 shows the cross track error for the three straight sections of Track 1, though they are too short to provide statistical information about this measure. The graphs are shown from the point at which Wayamba has designated it has reached the current waypoint and turned onto the new track leg. The initial curve therefore shows how the cross track error changes as Wayamba adjusts its heading and begins to reduce its deviation from the expected track. The initial values show that for legs 2 and 3, the track has been designed to take the vehicle’s ability to turn into consideration. In both cases the vehicle overshoots the desired track by approximately 1 metre, but within 20 seconds the autopilot has reduced the cross track error to less than 0.5 metres. Thereafter the autopilot maintains the error within this half metre envelope, with no obvious oscillations taking place. Further analysis of the cross track error will be conducted in future with Wayamba following much longer and repeatable track legs to provide more statistical information. It is the intention eventually to develop an in-house track-following algorithm that can be adapted in real time for path-planning or obstacle avoidance, rather than relying on the Spectre’s inbuilt algorithm.

Figure 18 shows a second track that was conducted on a subsequent trial day from the north wharf of Corio Quay. Track 2 was a rotated and scaled version of the original track to match the different orientation. The RCW software did not allow for the new mission profile to be rotated without some degree of scaling, though this has since been corrected in a newer version of RCW. It should also be noted that after the first straight segment the track following mode was interrupted briefly using manual control to steer away from a temporary obstacle before track following was re-enabled to run the second leg. During this track the vertical thrusters were not used by the autopilot, leaving the bowplanes to be used for pitch, roll and depth control. This setting was enabled in the autopilot until Wayamba dropped below 0.5 metres per second. These results indicate that the greater separation between the tracks, and the slower turns were more accurately negotiated by the autopilot. The forward velocity was minimally impacted by the corners, and the control of depth was more accurate than the track recorded on the previous day. It is clear from these results that using the bowplanes alone does allow for accurate control of Wayamba when operating at higher speeds, as the pitch and roll results are similar for both tracks.

It is possible to use the RCW interface or direct NMEA commands to change the control set points at any time whilst the vehicle is following the track; however this cannot be automated using the RCW generated tracks alone. For example increasing speed to 1 metre per second at waypoint 2, then decreasing to 0.5 metres per second at waypoint

\textsuperscript{4}More sophisticated analyses, not undertaken here, would take account of both cross-track error and variation in heading. The reason for assessing performance in terms of both measures has relevance to sonar-based survey. Drift away from programmed track lines can cause ‘holidays’ \cite{8} and rapid changes in heading can either degrade sonar imaging or cause targets to be missed \cite{9}.\unclass}
Figure 15: Example of Wayamba operating in track following mode to follow Track 1
Figure 16: Data collected during track following for Track 1
Figure 17: Cross Track error for straight segments of Track 1
Figure 18: Example of Wayamba operating in track following mode to follow Track 2
Figure 19: Data collected during track following for Track 2
3 would require an operator or external mission management system. More complicated three dimensional manoeuvres would also require a custom control program or WANE node to be developed to achieve this. This could be done in conjunction with an RCW programmed track using SSSCP commands, or could be fully implemented in NMEA by utilising the XTB commands to provide the cross track error and heading parameters for the current track.

The results shown here are representative of a number of other tracks that were followed during the sea trials. The operators soon became comfortable with the accuracy of the vehicle’s location and behaviour when it was not visible, relying upon the combination of the location on the map and the sonar data to avoid the edges of the quay and other obstacles. Care was also taken to ensure that turns, whether automated or manually controlled, would not entangle the tether cable. The results clearly indicate that this mode could be used to control Wayamba’s manoeuvring in conjunction with an automated mission controller to increase the automation of the entire system.

4.3 Hover Control

The automatic tuning process required to optimise the controller on the physical vehicle was initially performed with Wayamba in DSTO’s test tank to allow for preliminary tests to be conducted on the autopilot’s hover control, or Dynamic Positioning (DP) functions. DSTO’s fresh water test tank measures 10x10x6 meters, providing sufficient space to test the control requirements for hovering and the tank’s water recirculation system provided a small simulated current for the vehicle to respond to. Wayamba was loosely tethered on four corners with ropes to limit its travel, preventing it from hitting the sides of the tank, while still providing unimpeded freedom to perform the tests. After some initial checks the auto tune process was conducted in the sequence outlined in Section 3.3, with the exception of speed control due to space constraints. The Spectre autopilot performed very well in this controlled environment, with the subsequent sea trials at Corio Quay replicating this accuracy after performing the automatic tuning process for open water, including optimising the speed control. This staged evaluation was conducted to both increase proficiency in the operation of the system, and because the vehicle was now in salt water the buoyancy had been adjusted. Buoyancy and the trim of the vehicle proved to be a critical aspect in the tuning of the controller, the accuracy of the control in the hover mode was high enough for the logs to show quantization limits of the PHINS unit’s location estimate, which is 10mm and output at 100hz [7].

During the open water trials the hover modes were regularly used, with very accurate positioning possible during calm conditions which did not approach the performance limits of Wayamba’s actuators. These results were provided in H-Scientific’s report on the detailed analysis of the autopilot’s control in hover mode [10], which is summarised in Table 4. The best hover results were achieved on the first day of sea trials, the 3rd of November, under remarkably still conditions in Corio Quay. The hover mode was activated to maintain a set location with a specified heading (DP1). In this hover period, the location was maintained with standard deviations of 14mm in the X direction, 13mm in the Y direction and 5mm in depth, with 0.07 degrees in heading variation recorded while at a depth of 2.1 meters for 9.6 minutes. Such small variations would be difficult to detect
without the measurement accuracy of Wayamba’s PHINS unit, though Wayamba’s log files demonstrated that with data obtained at 100Hz, the vehicle is stable enough for the quantization error in the PHINS measurement to be visible. The results obtained in this trial demonstrated that the autopilot can control Wayamba to hover at a set location with an extremely high degree of accuracy and stability, albeit under almost perfectly neutral environmental conditions.

Wayamba’s umbilical tether was identified as a limitation that restricted the use of modes DP0 and Area Dynamic Positioning (ADP0) due to the risk of the vehicle automatically turning into the current with disregard to the location of the tether, potentially leading to twists or entanglement. Care should also be used when combining the track following mode with a hover set-point at the end of the track. Depending on the vehicle’s speed it can overshoot the hover set-point, then the autopilot will put the vehicle into reverse to return to the location set point and could entangle the tether during this manoeuvre. This is a limitation that is manageable by the operator or mission control system reducing the speed prior to reaching the hover set point.

A detailed analysis was conducted by H-Scientific’s Henry Robinson [10], who attended the trials, of five different hover periods in DPH mode (Dynamic Positioning with a fixed heading) with pitch and roll control enabled and set to zero. The data were captured on the 2nd and 3rd of November and is summarised in Table 4. This table provides the time in minutes for which the hover mode was activated, the heading set point in degrees, the depth in metres, the standard deviation of the position in both X and Y directions as well as the depth in metres, the standard deviation of the heading in degrees, and the average activation percentage for the thrusters. This activation percentage will be negative when the thruster is forcing Wayamba down towards the sea floor. Because of the positioning of the thrusters, the forward vertical thruster is used to maintain the pitch of the vehicle, with a negative force pushing Wayamba’s nose towards the sea floor. The port and starboard thrusters have a more limited effect on pitch, but provide control over the vehicle’s roll. Where these thrusters are operating in opposite directions, they are counteracting Wayamba’s tendency to roll whilst hovering due to imperfect trimming.

**Table 4: Hover analysis conducted by H-Scientific [10]**

<table>
<thead>
<tr>
<th>Hover No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial Day</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Bumpers</td>
<td>on</td>
<td>on</td>
<td>on</td>
<td>off</td>
<td>off</td>
</tr>
<tr>
<td>time (mins)</td>
<td>9.2</td>
<td>8.0</td>
<td>9.6</td>
<td>25.9</td>
<td>15.6</td>
</tr>
<tr>
<td>Heading (degrees)</td>
<td>234.7</td>
<td>234.7</td>
<td>234.7</td>
<td>116.6</td>
<td>207.0</td>
</tr>
<tr>
<td>Depth (m)</td>
<td>1.48</td>
<td>1.50</td>
<td>2.10</td>
<td>Surface</td>
<td>3.16</td>
</tr>
<tr>
<td>Std Dev X (m)</td>
<td>0.070</td>
<td>0.019</td>
<td>0.014</td>
<td>0.026</td>
<td>0.037</td>
</tr>
<tr>
<td>Std Dev Y (m)</td>
<td>0.060</td>
<td>0.030</td>
<td>0.013</td>
<td>0.078</td>
<td>0.015</td>
</tr>
<tr>
<td>Std Dev Depth (m)</td>
<td>0.007</td>
<td>0.089</td>
<td>0.005</td>
<td>0.020</td>
<td>0.025</td>
</tr>
<tr>
<td>Std Dev Hdg (degrees)</td>
<td>0.273</td>
<td>0.137</td>
<td>0.070</td>
<td>0.954</td>
<td>0.364</td>
</tr>
<tr>
<td>Thrust levels</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Avg Fwd Vert (%)</td>
<td>-60.7</td>
<td>-61.0</td>
<td>-58.0</td>
<td>-41.5</td>
<td>-17.4</td>
</tr>
<tr>
<td>Avg Port Vert (%)</td>
<td>-14.0</td>
<td>-14.2</td>
<td>-13.7</td>
<td>-24.9</td>
<td>-22.3</td>
</tr>
<tr>
<td>Avg Stbd Vert (%)</td>
<td>14.0</td>
<td>14.2</td>
<td>13.8</td>
<td>-12.7</td>
<td>-22.9</td>
</tr>
</tbody>
</table>
The 3 periods of hover control analysed from the first trial day, the 2nd of November, were conducted as underwater station keeping. The standard deviations of the vehicle parameters show a high level of stability, with Wayamba remaining within 100 millimetres of the location set point with a heading deviation of less than a quarter of a degree. An analysis of the thruster usage shows that the front vertical thruster was continuously operating at 60% with approximately 28% differential thrust on the port and starboard thrusters maintaining a level attitude for Wayamba. This indicates that Wayamba could have been retrimmed to be remain level with less thruster use.

On the 3rd of November Wayamba was adjusted to remove the bumpers from the vicinity of the front bowplanes, requiring re-trimming. This allowed hovering to be achieved using less thrust to maintain level attitude, indicating a better standard of trim had been achieved. Two longer duration hover periods were analysed on the second day, shown as hover 4 and 5 in Table 4. These results again show a high degree of accuracy, with the location maintained within 100 millimetres, though the heading did vary by up to 1 degree. The thruster results for this day also show that all the thrusters are used to maintain the vehicle depth and counteract the vehicle’s positive buoyancy, but they were not significantly required to maintain level. It can also be noted that hovering on the surface, hover number 4, had only a slightly higher variation in the Y direction than the other hover conditions, and the heading variation was still under a degree. This indicates that the effect of the wind and waves had little detrimental effect on the hover mode in calm conditions, though this will become more significant in higher sea states.

Figure 20 is a screen shot of the plan view window of the RCW interface. It shows a zoomed in view of Wayamba in hover mode DPH (Dynamic positioning with Heading) for hover 3, which was held for approximately 9.6 minutes. In this display the centre of the triangle indicates the position of Wayamba, with the longer point indicating the vehicle’s current heading. The yellow triangle indicates the current position and orientation, with white triangles displayed every 50 seconds to give an indication of the changing position and orientation of the vehicle over time. Figure 20 therefore provides a history of the location and orientation of Wayamba, demonstrating the accuracy of this hover mode.

5 Discussion

This report has investigated the effectiveness of applying a commercial autopilot to increase the automation of DSTO’s UUV Wayamba. After the integration of the Spectre autopilot into the Wayamba platform was completed, a series of trials was conducted with the developer of the autopilot to tune its performance and investigate its control under a range of expected operational circumstances. Whilst the trials schedule did not permit enough repetition to provide a full numerical analysis, it did provide significant results to demonstrate the autopilot’s ability to precisely control the vehicle, as well as highlighting some of the potential problems associated with the use of commercial autopilots on Wayamba.

The integration of the autopilot into the Wayamba platform was conducted without requiring substantial changes to the existing software or hardware. This is in part due to the quality of the documentation of the autopilot, as well as its design to allow the
Figure 20: Dynamic positioning results in metre grid squares over a 9.6 minute period

system to use serial inputs and outputs that can be sent through Wayamba’s computer network. This allowed the autopilot to be initially installed on the dockside control system with a connection to send actuator commands through the operator’s computer using a WANE node. When the unit is integrated inside Wayamba’s hull (scheduled for late 2012), the autopilot will receive a data feed directly from the PHINS unit, and output actuator commands directly to the computer controlling the actuator. A software switch will also allow the system to switch between autopilot control and manual control if it is required, though the autopilot does also have its own E-Stop system to ensure safety.

The Spectre autopilot was developed alongside the RCW software that controls it, though a SSSCP or NMEA interface will likely provide a more useful interface with the mission management software that is to be developed for Wayamba. RCW creates an easily customisable interface with two windows. One provides an awareness of the vehicle’s orientation and activation levels as well as the control modes and set points, whilst the second window provides a map based view of the location to provide positional awareness. The operators found the RCW to be relatively straightforward to use with simple mouse clicks to adjust the control modes and set points. This provides a number of advantages over the current manual control method, which appears to be less accurate in achieving a given control condition, such as maintaining a heading, and requires constant operator input to do any maneuvering or maintain a depth below sea level. The map interface provides a good indication of location when a geo-referenced image is used as an overlay, though care is required to ensure this is accurate so that it does not mislead the operator on the vehicle’s true position. This map interface also allowed for the entry of waypoints to develop the track for the autopilot to follow. The entry of waypoints via mouse-click is very straightforward, though positioning these waypoints exactly requires more detailed operator input though a range of options in a pop up window. In due course it will be necessary to develop a formal mission planning tool for operating Wayamba autonomously, which will automate most of the RCW functionality. The initial version of the RCW
software also did not allow for the track to be rotated and scaled independently. Thus changing a calibration track to operate off a wharf that was at a different orientation to the original wharf was difficult to do accurately. This is reported as having been fixed in a software update, but is yet to be tested. Overall RCW provides a useful operator interface for manually controlling the vehicle behaviour through the autopilot.

The results presented in this report show the precision of the autopilot during a range of maneuvers, which has also allowed the vehicle characteristics to be determined more accurately. The autopilot demonstrated better precision at maintaining parameters such as heading, depth and speed than an operator could achieve using manual control. When Wayamba was operated in track following mode it maintained the track as well as depth and speed unless a programmed turn was too sharp, at which point the vehicle tended to lose some speed to achieve a smaller turn radius, which could also induce a small amount of roll to the vehicle. It is also observed that, when operating at a cruising speed of between 0.6 and 0.8 m/s around a track, the thrusters could maintain the required roll and pitch attitude slightly more accurately than using bowplanes alone, though the autopilot did have difficulty maintaining zero pitch when travelling forward at more than half speed. The control of speed worked effectively as both a percentage of maximum speed (DCAM mode), and maintaining water speed set point in an absolute sense. Using speed control, Wayamba even managed direct lateral motion without significant forward motion, though the configuration of the vehicle is not optimised for this manoeuvre, so such motion will be very inefficient.

Minor changes in configuration, such as removing guards from the bowplanes or attaching additional equipment, changes the vehicle’s performance characteristics, and therefore requires retuning of the autopilot’s control parameters. This can be achieved either by running through the automatic tuning process again, which may take up to 30 minutes, or by uploading pre-computed configurations that were obtained when the automatic tuning process was previously run in that vehicle configuration. The major changes occur in the PID coefficients for a given controller to make the manoeuvres more or less aggressive depending upon the effect of the vehicle configuration changes. In practice the changes are likely to be more important for accurate control of the vehicle speed as most other modes are less sensitive to changes and will generally have a degree of over actuation and a longer settling period before reaching the desired set point. Additional trials are needed to examine the extent to which configuration changes affect the control parameters; however we expect that the changes are likely to extend the time required to reach the desired set point. Thus Wayamba will still be controllable without re-running the automatic tuning process, but not as accurately or as efficiently. It is therefore advisable to have pre-loaded the parameters for each configuration that might be expected during a given mission and upload the relevant settings in a few seconds when the configuration changes, such as when a payload is released.

The trial also demonstrated that care needs to be taken by the mission planner and operator to consider the probable disposition of the tether cable throughout the mission. This is of critical importance as the autopilot does not consider the tether position. This is an especially important consideration when the hover mode is to be used. If the vehicle is allowed to find its own heading to minimise energy use, it could potentially turn in such a way as to add a twist in the tether. If the area hover mode is selected, then the vehicle will move within a predefined radius, increasing the likelihood that it may reverse and create
additional problems with the tether. When the single point hover mode was selected and
used with a constant heading being maintained, the vehicle demonstrated that it could
maintain its position within a 10 centimetre radius for over 25 minutes (as measured by the
vehicle’s own sensors). Such capability could be very useful during launch and recovery
operations. DSTO is currently investigating, with collaborative partners, concepts for
short-range, high-bandwidth through-water communications. Having the ability to hover
with this level of precision could significantly enhance the effectiveness of data upload
missions using communications of this form.

The Spectre autopilot has demonstrated that it is capable of accurately controlling a
highly manoeuvrable UUV such as Wayamba. This accuracy will improve the ability of
Wayamba to perform repetitive tasks for data collection, such as scientifically investigating
the effects of attaching other devices. It will also allow for a greater degree of operator
confidence in the accuracy of manoeuvring Wayamba underwater, particularly in confined
or cluttered environments, such as quay-side. It is however only the first step towards
the future goal of automation, which requires Wayamba to perform a range of other tasks
including sensor processing, mission management and safety procedures. Key aspects of
processing sensor data include identifying internal system health and safety concerns such
as power usage, temperature extremes or water leaks, as well as finding external obstacles.
Such information must be analysed by the mission management software to conduct safety
assessments and path planning to maximise the probability of success for a mission. If
Wayamba is powered by batteries such components will have to work very reliably, as
it will be difficult to monitor or control the vehicle effectively without the tether which
currently provides high speed optical fibre communications.

6 Conclusion

The Wayamba project has progressed for over a decade in developing a highly manoeu-
vrable underwater platform and the software required to operate it. The current Wayamba
platform is a remotely operated vehicle which is capable of performing a range of under-
water and surface based tasks; however its capability is limited by its tethered connection
for power and manual operator control. Whilst the supply of power can be provided by
installing batteries, reducing the requirement for operator interaction through automa-
tion requires a number of steps including accurate control for manoeuvring, adjusting the
track planning for the local environmental factors and adaptation of the mission based
upon sensor analysis. The autopilot addresses the step of accurate manoeuvring, includ-
ing the accuracy of manual control, though other software is required to further increase
the level of system automation if the dedicated communications link is to be removed.

This report has detailed how the Spectre autopilot unit provides the ability for Wayamba
to have accurate control of a range of the vehicle parameters, providing precise manoeu-
vring capability. This will allow it to achieve its given tasks, such as track following, tran-
siting to a given location, or maintaining a hover position. The trial results demonstrate
that the autopilot can utilise a basic model of Wayamba’s actuators with an automatic tun-
ing process to determine how the actuators should be used for controlling the platform.
The autopilot can be calibrated for changes in configuration of the Wayamba platform
which do not adjust the vehicle’s actuators by using the automatic tuning process. This
process can often be conducted within twenty minutes just prior to a mission. It should
also be noted that calibration files which have already been tuned for a particular config-
uration can be uploaded within seconds to allow the vehicle to quickly adjust parameters
depending upon operational conditions, such as using the Murula module to deploy off-
board sensor systems. The operators indicated that the simulated vehicle performance was
similar to the real vehicle performance, indicating that training on the simulator would
be beneficial to performance operating the real vehicle in many situations. The surface
conditions are not simulated and could lead to significantly different operations, especially
during high sea state conditions.

The accuracy of control which is achieved by the autopilot increases the repeatability
of manoeuvring, which can be utilised by DSTO’s research programs to increase the ef-
ectiveness of scientific investigations. This allows for the use of a standardised track, or
tracks, which can be repeated when Wayamba or its payloads undergo changes in their
configurations. This will provide increased data to be obtained about a range of vehicle
characteristics such as power consumption, buoyancy, or drag, as well as the development
of models of vehicle performance to better inform the mission management system.

The increase in autonomy provided by the autopilot now allows the operator, or a
mission control system, to set the vehicle parameters using RCW or the WANE software
via NMEA commands and observe Wayamba’s motion, without the operator continually
adjusting the motion through a hand held controller. This is an important step towards
a truly capable AUV, although it needs to be integrated within a mission management
module so that it utilises sensor processing for obstacle avoidance, adaptable motion path
planning, and other software modules to reliably achieve its tasks without requiring user
interaction. The developers of the autopilot also indicated that the same autopilot has been
used on surface craft, indicating that similar results might be achievable in this domain
using an affordable commercial autopilot. If more widely adopted, the flexibility of the
autopilot could allow for navies around the world to use similar hardware and software to
develop and prototype a wide range of novel maritime concepts and platforms.

Acknowledgments

Our thanks go to Henry Robinson of H-Scientific who helped us to smoothly integrate
the Spectre autopilot into the Wayamba system and helped us to gain a more thorough
understanding of how to use it effectively.

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<td>This report documents the successful integration of a commercial autopilot (a “Spectre” system from H-Scientific) into DSTO’s Wayamba unmanned underwater platform, which was tested in sea trials during November 2011. The Spectre is a closed loop controller that, once tuned and matched to a vehicle, affords independent control of vehicle parameters such as pitch, roll, heading and speed, as well as allowing more complex manoeuvres such as track following, hovering and lateral motion. The autopilot uses an automatic tuning process to set its control parameters, refining a user-provided allocation table representing the gross effects of the vehicle’s actuators on its motion. While the resulting control may not be provably optimal, this tuning process can take place without a detailed hydrodynamic model. In Wayamba’s role as a delivery system and testbed for large payloads, vehicle dynamics and response may change considerably between or even during missions. The Spectre allows tunings for various configurations to be stored and switched online, for example when a payload is deployed. As an illustration of the degree of control demonstrated in the trial results, the Spectre was able to keep Wayamba hovering for some 25 minutes with a standard deviation in position less than 10 centimetres, and a standard deviation in heading of less than one degree.</td>
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