Abstract—Autonomous underwater vehicles (AUVs) are increasingly being deployed in the study of inshore coastal marine habitats. Combined with shipboard systems, scientists are able to make in situ measurements of water column and benthic properties. In CSIRO autonomous gliders are used to collect water column data, while surface vessels are used to collect bathymetry information through the use of swath mapping, bottom grabs, and towed video systems. Although these methods have provided good data coverage for coastal and deep waters beyond 50m, there has been an increasing need for autonomous in-situ sampling in waters less than 50m. In addition, the collection of benthic and water column data has been conducted separately, and requires scientists to post-process data in lab. A new system was needed to allow for in-situ observations of both benthic habitat and water column properties in shallow waters. CSIRO has developed an AUV (Starbug X) to deliver enhanced observation capabilities of both benthic habitats and water column properties. The system is equipped with a range of built-in sensors as well as two sets of cameras allowing for the collection of multi-parameter observations. Crucially, the in-situ collection of benthic and water column data allow scientists to better relate water quality to changes in the benthic habitat. This paper discusses the development and use of a software tool that streamlines the analysis and visualization of vehicle multi-channel data stream; the STarbUg Analysis & Reporting Tool (STUART). In addition, future developments in vision based navigation, mission planning, and the integration of water column data is discussed. Finally the paper discusses how Starbug X and future STUART development fill a much needed capability gap in CSIRO’s existing integrated ocean observing systems.

Keywords—Starbug X, STUART, AUV, data, analysis, imaging

I. BACKGROUND

In an effort to better understand the impact of human activities and climate change on reef and coastal marine habitats, scientists need to monitor areas at risk. This is particularly important in shallow waters where there can be abundant marine life and marine biodiversity. Benthic characterisation and mapping provides scientists with a basic tool for understanding the dynamics of these seafloor habitats. In the CSIRO Oceans and Atmosphere Business Unit (OA) scientists are actively engaged in this field and are particularly interested in conducting surveys of three benthic habitats; seagrass, kelp and coral reef areas.

The surveying of coastal seagrass beds is particularly critical as they are difficult or impossible to survey using remote sensing applications. Currently in Moreton Bay, Queensland, environmental monitoring of seagrass is focused on “seagrass depth range sites” where divers perform surveys of the seagrass bed in particular locations by swimming parallel transects across the depth gradient, to establish the shallowest and deepest margin of the seagrass beds. At present, only limited transects are performed at each location, and are not able to provide complete coverage of the region.

In Western Australia, CSIRO is involved in a number of studies investigating the dynamics of kelp forests. Currently, video and digital still images are collected by divers along linear transects and across smaller 25 x 25 m sites for complete coverage mapping. The challenges associated with this type of survey is the geo-referencing accuracy of the images, limited dive times due to depth and available air supply, as well as the weather and other operational conditions as these sites often encroach the surf zone.

Traditionally, a majority of coral surveys are video or digital still collections of transects undertaken by researchers via diving, or by snorkelling (as per the seagrass and kelp surveys). These suffer the same challenges and limitations as the other monitoring scenarios. In recent years however the use of AUVs to collect large area coverage maps using sonar and images for coral reefs has become more common, although these tend to be in deeper water and require larger support vessels.

Each of these surveys pose some unique challenges for scientists. Sites of interest in Australia are often turbid, highly tidal and located in areas of surf or surge which make using conventional methods quite limiting. Additionally, there are often significant risks of attack from sharks and crocodiles making traditional diver-base survey dangerous. In these situations it is apparent that an automated data acquisition and analysis system offers huge potential to improve the accuracy, increase replication, increase the types of data collected during surveys and reduce risks to researchers.
II. STARBUG X AUV SYSTEM

The Starbug X AUV was developed to provide enhanced observation capabilities of both benthic habitats and water column properties. Starbug X is the third generation AUV first developed by the CSIRO for benthic characterisation using vision based navigation. The core platform was designed around the use of a pair of stereo forward and downward facing cameras, providing images of the benthic environment while allowing for enhanced dead reckoning using the resulting photometry. Navigation is also aided through the use of differential GPS and a MicroStrain IMU. Although the original Starbug system allowed for the use of external sensors, the base platform did not provide any built-in science sensors.

Starbug X was designed to provide enhanced science capabilities in addition to improvements in the vision systems. The two sets of stereo cameras were upgraded to HD resolution allowing for improved images of the benthic environment. This allows scientists to not only look at bottom coverage, but identify specific benthic communities; such as sea-grass or corals in the images. Complementing the vision system is a suite of oceanographic quality sensors which have been integrated into the platform. A Seabird CTD, Wetlabs ECO triplet (providing CDOM, Chlorophyll-A and Backscatter 700nm readings) and Aanderaa oxygen optode provide continuous data on water column properties. The sensor suite is identical to that used on Teledyne Webb Gliders used by the CSIRO and moorings deployed by the Integrated Marine Observing System (IMOS) in Australian coastal waters. This allows for completely inter-operable data sets across all CSIRO and IMOS deployed systems. This allows for completely inter-operable data sets across all CSIRO and IMOS deployed systems. In addition to the built-in science capability, Starbug X supports the use of up to three additional external sensors. Most notably, the use of a Licor irradiance sensor, and a Satlantic nitrate sensor have been considered for use with the Starbug X platform.

Unlike glider systems, Starbug X is actively propelled through the use of thrusters which allows for increased mission planning flexibility. Most notably, the system is able to conduct bottom tracking transects at low altitudes (down to 0.1m), and vertical profiles (either vertical or with a specified glide angle). The fully assembled system is small and lightweight, with a length less than 1m and a total mass in air less than 30kg. This allows the system to be deployed from small vessels, and to operate in very shallow waters such as coral reefs. Although Starbug X was chiefly designed to operate in shallow water from the surface to 30m depth, an operational depth rating of 100m increases its reach offshore, and allows for increased mission planning flexibility; such as surveying of coastal shelves.

The Starbug X AUV provides a unique capability and flexibility in the collection of both benthic habitat and water column information. The enhanced suite of oceanographic sensors provide a rich data set in shallow coastal waters less than 10m deep, which are currently not readily accessible by commercial AUV systems. Crucially, the in-situ collection of benthic and water column data allow scientists to better relate water quality, to changes in the benthic habitat. A complete description of the design of the Starbug X system can be found in [1].

III. FIELD TRIALS

A variety of science field trials of Starbug X were conducted in Moreton Bay near Brisbane Australia, and in the Derwent River in Hobart Australia. Deployments were undertaken either from the shore or from small vessels. A range of shallow water missions were undertaken including linear transects, surface to depth profiles and grid patterns. The system was operated in depths ranging from 1 m to 20 m with mission time from a few minutes to several hours. The sample data collected from the field trials were used as representative data sets in the development of software analysis and reporting tools.

IV. DATA ANALYSIS AND VISUALISATION

Following the sea trials, it became apparent that there was no rapid way to organise and review the data at the end of each mission. The time and effort required to process and review data between missions lead to long turn-around times for the system, as scientists and technicians worked through the data from each mission before redeployment. In order to make mission data more accessible, the STarbUg Analysis & Reporting Tool (STUART) was developed to quickly extract mission data and create a report which would provide users with a way to quickly glance at the mission and determine whether there may be any details of particular interest. The tool was developed using the MATLAB programming environment to allow for quick and easy manipulation and visualisation of large data sets.

Figure 1: STUART software structure
A. In-Situ Sensors

In developing this tool, the science and engineering data streams are managed separately. For the science stream, it was decided to develop a short A3 sized report which showed a mission map along with some of the most important environmental measurements plotted against time. The engineering tool on the other hand, was developed to provide an opportunity for a more detailed review and analysis of the data. This is because the engineering data is only likely to be used when attempting to diagnose any issues or errors which may appear in the science data.

Starbug X logs each sensor data stream to separate text files as part of its data collection process.

Sensors for collecting scientific data include:
- Conductivity Temperature Depth (CTD) sensor, for measuring the physical properties of the water body
- ECO-triplet, for monitoring the presence of organic matter including chlorophyll, coloured dissolved organic matter and light scattering
- Dual LI-COR sensors for measuring light intensity above and below the craft
- Optode sensor, for measuring oxygen content of the water

Sensors for measuring engineering data included:
- ImageData, dual forward facing cameras
- Altimeter
- Position data (estimated and intended variables)
- IMU, inertial measuring unit records rates, accelerations and fields (measured)
- Orientation, rates, accelerations and fields (intended)
- AuvData, Motor usage, motor forces, motor currents, battery status, position and orientation information
- GPS Surface, Global Position System readings from towed float (if attached)
- GPS, Onboard GPS readings (when craft is surfaced)

B. Data Tools and Reports

The STUART software suite consists of a series of tools which provide separate and distinct functions. A breakdown of these tools and their associations is depicted in figure 1. STUART is divided into three folders which contain the mission data, science scripts and engineering scripts respectively. The raw mission data is located within the data folder. STUART collates data and processed data is saved as tables in a comma separated variable (.csv) format back in their original mission folder. When the plotting and reporting tools are run, the science reports are saved in an output folder within the science folder and the engineering plots are saved in an output folder within the engineering folder.

C. Science Visualisation Tools

The most useful output of the STUART tool set is a series of plots and maps which quickly summarize the key data related to the Starbug X mission. Samples of data collected for sea trials in Hobart can be seen in figures 2, 3, 4 and 5. The first of the maps is a view of the Starbug X track overlaid on a Google Maps satellite image of the area. The second of the maps overlays this mission segment with all other missions in the survey work. These two maps enable the users to quickly and easily identify the mission.
location in relation to other transects and relevant land and sea features. Accompanying these maps is a series of time aligned plots which show key science data from the mission. All the plots are aligned against mission time and depth with serve as good indicators of mission progression. Outside of the reporting, the science visualization tools allow users to create their own data plots using arbitrary axes, and are even able to plot data sets against each other for comparison.

D. Engineering Visualisation Tools

Starbug X collects a very large set of engineering variables which describe the performance of the system. As this dataset is quite dense and specialised, a separate tool was developed to allow navigation and interaction with this data which is focused towards technical operators, problem solving and mission planning. The engineering tools allow for manipulation of data, zoom function, custom axes and multiple overlaid data plots. This is a powerful tool in identifying engineering issues and operational anomalies.

An example of a common analysis is shown in figure 5, where Starbug X battery voltage and current are overlaid on a single plot. This plot shows the decrease of battery voltage along the mission duration as expected. It can be seen however that there are momentary periods when the current level drops and the voltage stabilizes. This is a good indicator that the thrusters have stopped and a useful prompt for technicians to further review logs. This is especially the case when missions complete correctly and provide no outward indications to users that an anomaly has occurred.

E. Imaging

Data from each of Starbug X’s four cameras are collected and stored separately onboard as individual image files. Scientists use this data for a variety of purposes but mainly for benthic studies and ecosystem assessments [2,4]. CSIRO scientists employ a variety of image processing tools on the collected image streams to derive data relevant to their science needs. Due to the size of these datasets it can be time consuming identify areas of interest, particularly in reference to other allied data streams. To improve the accessibility of these data an imaging tool was developed within STUART that allows users to view images based on an interactive map of the AUV track. A sample of this can be seen in figure 6.

V. CONCLUSIONS AND FUTURE WORK

CSIRO developed a small portable AUV, Starbug X, to provide a platform for benthic and water column studies. In supporting the delivery of a large and varied suite of sensor data, CSIRO developed a series of data processing and analysis tools called STUART. These tools enable both quick and efficient reporting of key science data, and an interface with which to conduct extensive review of a broader range of both science and engineering datasets. The tools allow for both raw data review but also a set of visualization tools to enable cross comparison of data streams and quick identification of areas of interest and operational anomalies. These tools have enhanced the delivery of science data from Starbug X and allowed for easy identification of engineering data anomalies.

Development work on STUART is ongoing. The tools are being expanded to provide a broader range of metrics to quickly evaluate the systems performance. The data analysis and metrics will eventually be combined with the Starbug X mission planning tools to allow for intelligent mission planning based on previously observed data. This would for example allow for Starbug X to identify and target features of interest (such as thermoclines and anoxic zones) during
future missions. Starbug X data could also be combined with shipboard data from a surface vessel to further augment its datasets and situational awareness. All these data enhancements would also enable a set of enhanced engineering tools which would allow for automatic error and anomaly detection to aid technicians in diagnostic and maintenance work.

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