Towards Autonomy: A Recommender System for the Determination of Trim and Flight Parameters for Seagliders

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Abstract

Currently, pilots maximise the performance of Seaglider underwater gliders by manually selecting their set-up parameters. Building on existing procedures based on the assumption of steady-state motions, a recommender system for the trim and flight parameters has been developed to aid trainee pilots and enable round-the-clock operations. The system has been validated with data from 12 missions run in waters off the United Kingdom and Australia, representative of a range of oceanographic conditions. The recommended trim parameters present a maximum difference of 14% from the values selected by the pilots, whereas pilots are found not to change the flight parameters. Additionally, suggestions are made to improve operational practices to further improve the accuracy of the recommender system. As a result, the developed system is expected to greatly help trainee pilots achieve expertise in a much smaller time frame than standard practice. Additionally, thanks to its high precision, the recommender system can be used to autonomously select the trim and flight parameters of Seagliders for night operations in the future.

Keywords: Autonomous underwater vehicle (AUV), underwater glider, system identification, recommender system

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1. Introduction

Underwater gliders (UGs) represent a type of autonomous underwater vehicles (AUVs) whose vertical motion is obtained through changes in their buoyancy and is converted into horizontal motion through wings (Rudnick, 2016). As a result, they move in a characteristic vertical zigzag pattern or profile. Although they move at slow velocities, their propulsion system, which consists only of a variable buoyancy device (VBD), roll and pitch control mechanisms and sometimes a rudder, is very efficient and as a result UGs may be deployed for months in an area of operation. Therefore, since the first conceptual description in the visionary article by Stommel (1989), UGs have now become a fundamental tool for the study of the oceans (Rudnick, 2016). Not only are they used to study large-scale effects, e.g. boundary currents and the regional effects of climate variability, but also smaller scale effects like mesoscale and submesoscale features such as fronts and eddies (Rudnick, 2016). Thorough reviews of UG technology with a focus to oceanographic applications may be found in Davis et al. (2003), Wood (2009) and Rudnick (2016).

The National Oceanography Centre (NOC) in the UK operates a fleet of UGs for the study of the oceans, collaborating with the Scottish Association of Marine Sciences and the University of East Anglia. As part of the Oceanids project funded by the Industrial Strategy Challenge Fund[1], the NOC is developing a new command-and-control system for efficient marine autonomous systems fleet management. The aim of the system is to facilitate the operation of the ever-increasing fleet of AUVs. As part of this work, a recommender system for the selection of the trim and flight parameters of UGs is highly desired.

A recommender system provides users with suggestions on the products, services and information that best meet their needs (Aggarwal, 2016). Nowadays, the most familiar types of recommender systems are based on machine learning and can be found on internet platforms for the streaming of music and videos or the selling of products. Nevertheless, recommender systems are also found in the aerospace industry to help pilots with decision-making tasks for increased safety, as shown for instance by Dao et al. (2015), Bouzekri et al. (2017) and even the patent by Kim et al. (2017). The role of pilots of UGs is different from those of commercial aircraft: UGs are autonomous vehicles

[1] `https://noc.ac.uk/projects/oceanids`

that can perform a specified mission independently. However, the pilots need to correctly determine the UG's trim and dynamic parameters and send them to the UG remotely by satellite communication so that they may be implemented onto the on-board controller (IRobot, 2012). Therefore, similarly to the aerospace industry, the recommender system would support rather than automate the operators' decision making. Thus, the recommender system would return recommended values to the pilots within the fleet management software. However, pilots would be still able to overwrite the system so that it would not represent fully autonomous operation. Initially, the recommender system may help trainee pilots to determine the correct set-up of UGs. Once the system has been proven to be effective and robust, it may be used during night time and to help expert pilots track the operation of multiple UGs.

This article focuses on Seagliders, a type of UG developed originally by the University of Washington and first described in Eriksen et al. (2001). Seagliders are actuated only by a VBD and pitch and roll control mechanisms, which work by shifting and rotating the battery pack. The glider has a shape that is hydrodynamically optimised for least drag at its operating speed of approximately 0.25 m/s horizontal velocity, which is achieved through its wings. Seagliders are rated for depths of 1,000 m and a deeper water version has also been developed, the Deepglider, which can dive up to 6,000 m deep (Osse and Eriksen, 2007).

Although UGs may perform steady-state spiralling motions as shown by Zhang et al. (2013), the NOC runs missions with the Seagliders performing the classical sawtooth profiles in the vertical plane. In order to ensure high quality of the scientific measurements, a symmetrical dive pattern is desired, i.e. the Seaglider should present a similar mean glide slope for both dive and climb and little standard deviation (IRobot, 2012). Additionally, whereas the UG is designed to roll to achieve the desired yaw angle, roll motions severely affect the measured scientific data for up to 12 s after the roll control is set to zero (Frajka-Williams et al., 2011). Therefore, it is particularly important to trim the UG correctly. Procedures for the determination of the centres of the VBD, pitch and roll control mechanisms have been developed by Williams et al. (2008) for Slocum UGs, which are described in Webb et al. (2001) and Schofield et al. (2007), using system identification strategies on the gliders' deployment data. Similar strategies have been created by the developers of Seagliders at the University of Washington and these practical solutions can be found in the training manuals for pilots, e.g. the one by IRobot (2012). Furthermore, the control system on-board the Seaglider relies on a dynamic model of the UG, similar to the one described in Leonard and Graver (2001). In order to improve the performance of the UG, it is important to determine the correct model parameters, which are typically labelled as regression parameters (as they are obtained through a regression process) (IRobot, 2012) but are referred to here as flight parameters. Graver and Bachmayer (2003), Graver (2005) and Williams et al. (2008) obtained the lift and drag coefficients for a Slocum UG assuming planar motions, while Merckelbach et al. (2010) extended these methods to estimate vertical water velocities. Eriksen et al. (2001) developed a similar iterative procedure to obtain the lift, drag and induced drag coefficient for a Seaglider based on the equations describing its steady-state motion representative of its low-drag design. This process has been extended to the additional determination of the UG's compressibility, reference volume and thermal expansivity in Frajka-Williams et al. (2011) for the estimation of vertical currents based on the Seaglider's measurements.

Although innovative control strategies for UGs have been developed since the development of Seagliders, e.g. as described by Mahmoudian and Woolsey (2008), Hussain et al. (2011) and Li and Su (2016), the aim of the fleet management software being developed by the NOC is to optimise the UGs' performance without modifying the control software installed on the devices. As a result, the recommender system will be limited to the determination of the trim and flight parameters of Seagliders based on the analysis of live-stream data. Additionally, a robust implementation is desired in the short term. As a result, an evolution of the well-understood methods based on the equations of motion of a Seaglider under planar steady-state motions is preferred over machine-learning methods. In fact, since the determination of the trim and flight parameters is iterative even for pilots, apprenticeship learning strategies, as for instance described in Abbeel et al. (2010) may not be used successfully in this application.

The methods for the determination of the trim and flight parameters are developed using data from actual Seaglider deployments, extending previous work in Anderlini et al. (2019). Additional data were requested from the Australian Integrated Marine Observing System (IMOS) to assess the performance of the recommender system for a wide range of deployment sites, surface water temperature and Seaglider devices. Firstly, the determination of the centres of the trim and roll centres is improved with the analysis of raw control points. Then, the estimates of the flight parameters for different dive cycles are smoothed out through improved data cleaning and a larger moving window. Finally, a greater number of missions are analysed to assess the performance of the recommender system against professional UGs' pilots. The following sections will describe the data employed to develop and test the recommender system, the generated procedure followed by a comparison of the output of the recommender system against trim and flight parameters selected by the pilots.

2. Seagliders Data

2.1. Seagliders

During a deployment, a Seaglider, shown in Figure 1, stores a number of time signals and log parameters. In this study, only the time signals used directly in the control of the UG are of interest, rather than the scientific measurements which are the UG's primary mission objective. The basic time series signals can be seen in Table 1, while Table 2 shows the signals derived from the elementary ones. A right-hand-side reference system is used, with positive vertical displacement being upwards. The mean sample period for all deployments is approximately 30 s. Ranges for the basic variables can be seen in Table 1 as taken from deployments and IRobot (2012). Seagliders have a typical horizontal velocity of 0.25 m/s and vertical velocity of 0.1-0.15 m/s.

Figure 1: Seaglider UG at the NOC. The antenna has been removed for storage.

Table 1: Basic time series signals used in the recommender system with corresponding typical ranges. The control input variables are expressed in analogue-to-digital counts (0-4095) and their limits are taken from IRobot (2012).

Signal	Symbol	Unit	Typical Minimum Value	Typical Minimum Value
Time	t	[s]	0	18,000
Vertical position	z	[m]	0	1,000
Roll angle	ϕ	[°]	-40	40
Pitch angle	θ	[°]	-40	40
Yaw angle	ψ	[°]	-180	180
Water density	ρ	[g/cm^3]	1.000	1.0275
Water pressure	p	[dbar]	1	101.5
Water temperature	T	[°C]	2	30
Roll control	ϕ_c	[°] or [A/D]	150 A/D, -52°	3833 A/D, 52°
Pitch control	θ_c	[cm] or [A/D]	70 A/D, -10.3 cm	3352 A/D, 10.3 cm
VBD volume	V_{vbd}	[cm^3] or [A/D]	205 A/D, 557 cm^3	3510 A/D, -266 cm^3)

Table 2: Derived time series signals used in the recommender system.

Signal	Symbol	Unit
Buoyancy	B	[N]
Vertical velocity	$\dot{z}$	[m/s]
Vertical acceleration	$\ddot{z}$	[m/s^2]
Roll velocity	$\dot{\phi}$	[°/s]
Pitch velocity	$\dot{\theta}$	[°/s]
Yaw rate	$\dot{\psi}$	[°/s]

Example time series data for a typical dive profile can be seen in Figure 2. In Figure 2a, the typical sawtooth dive profile is clear from the Seagliders vertical position. In Figure 2b-c, during the dive, the vertical velocity, VBD volume, buoyancy, the pitch control and pitch angle signals are all negative and during the climb positive. As evident from Figure 2d, the Seaglider has to roll to maintain the desired heading. However, it is important to notice that the Seaglider turns in the opposite direction from its roll angle on the dive and in the same direction as its roll angle on the climb. This is due to the position of the centre of the hydrodynamic forces and the orientation of the hydrostatic, lift and drag forces in dives and climbs, as described in IRobot (2012). In all analysed deployments, a bang-bang control was used, where the battery pack is rolled by 40° until the desired heading is achieved. This causes significant noise in the other measurements, with a settling time of at least 12 s after the battery pack is rotated back to the zero position (Frajka-Williams et al., 2011). Despite the dynamic effects, bang-bang control is currently preferred in operational practices over smoother proportional control, since it results in lower power consumption and thus longer deployment duration.

UGs are sometimes trimmed incorrectly, especially during the initial stages of a deployment. In this case, the curve of the variation in depth with time is no longer symmetrical between dive and climb and it can show a non-linear shape, as shown in Figure 3. Additionally, as can be seen from a comparison between Figure 2a and Figure 3a, the glider spends more time at the apogee trying to pitch upwards and climb. This is clearly reflected in Figure 3b and Figure 3c, where both the vertical velocity and pitch angle signals do not respond linearly to changes in the control input. In the worst case scenario, the Seaglider has been observed to climb vertically to the surface tail up.

2.2. Steady-State Dynamic Model of a Seaglider

Zhang et al. (2013) have shown that UGs may be operated in a spiralling motion in steady-state conditions. Furthermore, as described by Rudnick (2016), UGs can provide measurements at a specific location by profiling vertically in the water against ocean currents with steep glide slopes. However, the data analysed in this article concerns the classical operation of Seagliders as profiling the water with a typical sawtooth pattern with a glide angle ranging from 10° to 45°, with 18° being the angle corresponding to greatest efficiency (Davis et al., 2003).

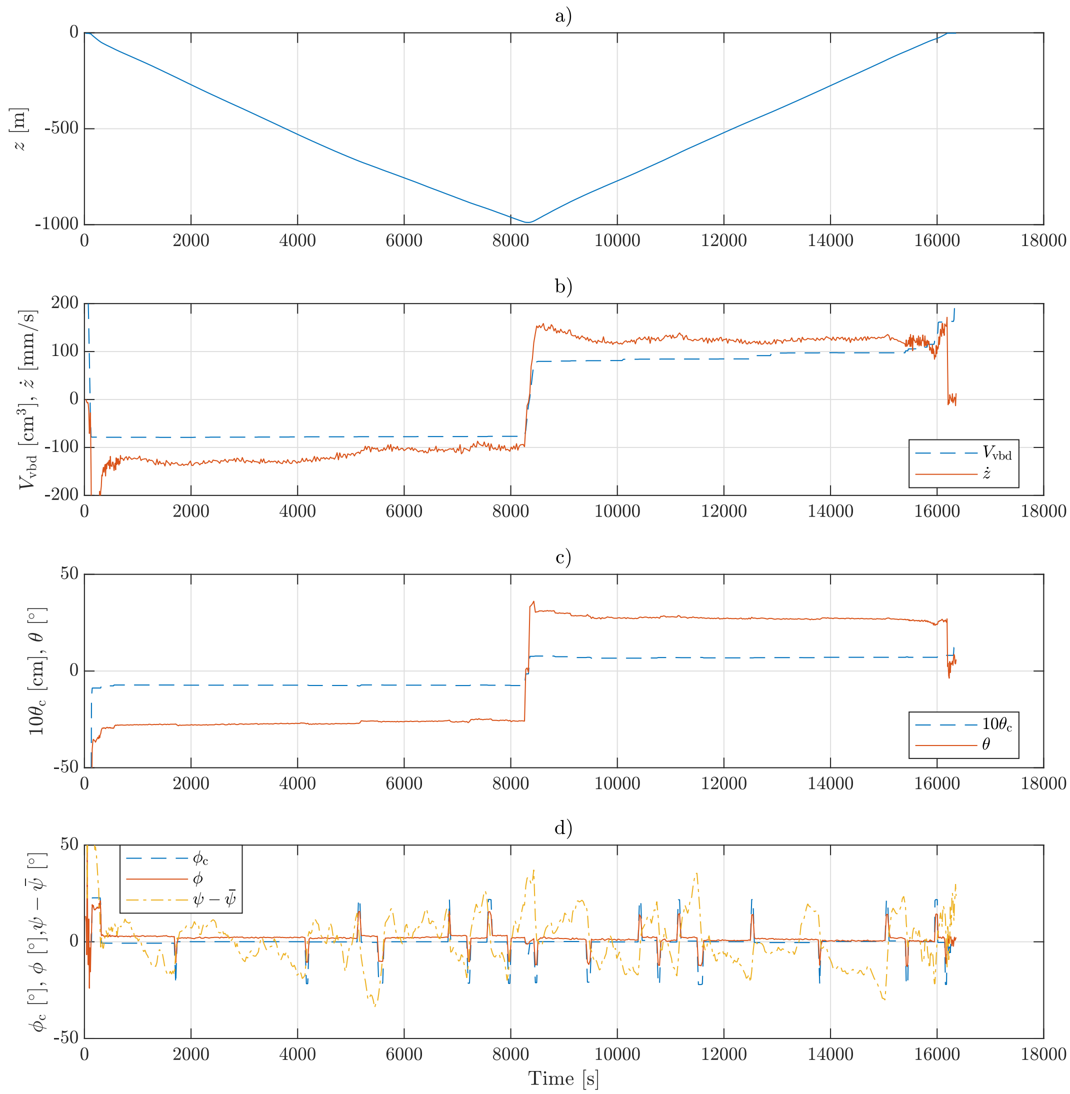


Figure 2: Example dive profile of a correctly trimmed glider.

The dynamic model of a Seaglider in planar motions in the vertical plane under steady-state conditions has been described by Eriksen et al. (2001) and Frajka-Williams et al. (2011). A free-body diagram is reported in Figure 4 for clarity. Under these assumptions and due to the hydrodynamic shape of the hull, the UG dynamics can be described by the following equations from a balance of forces:

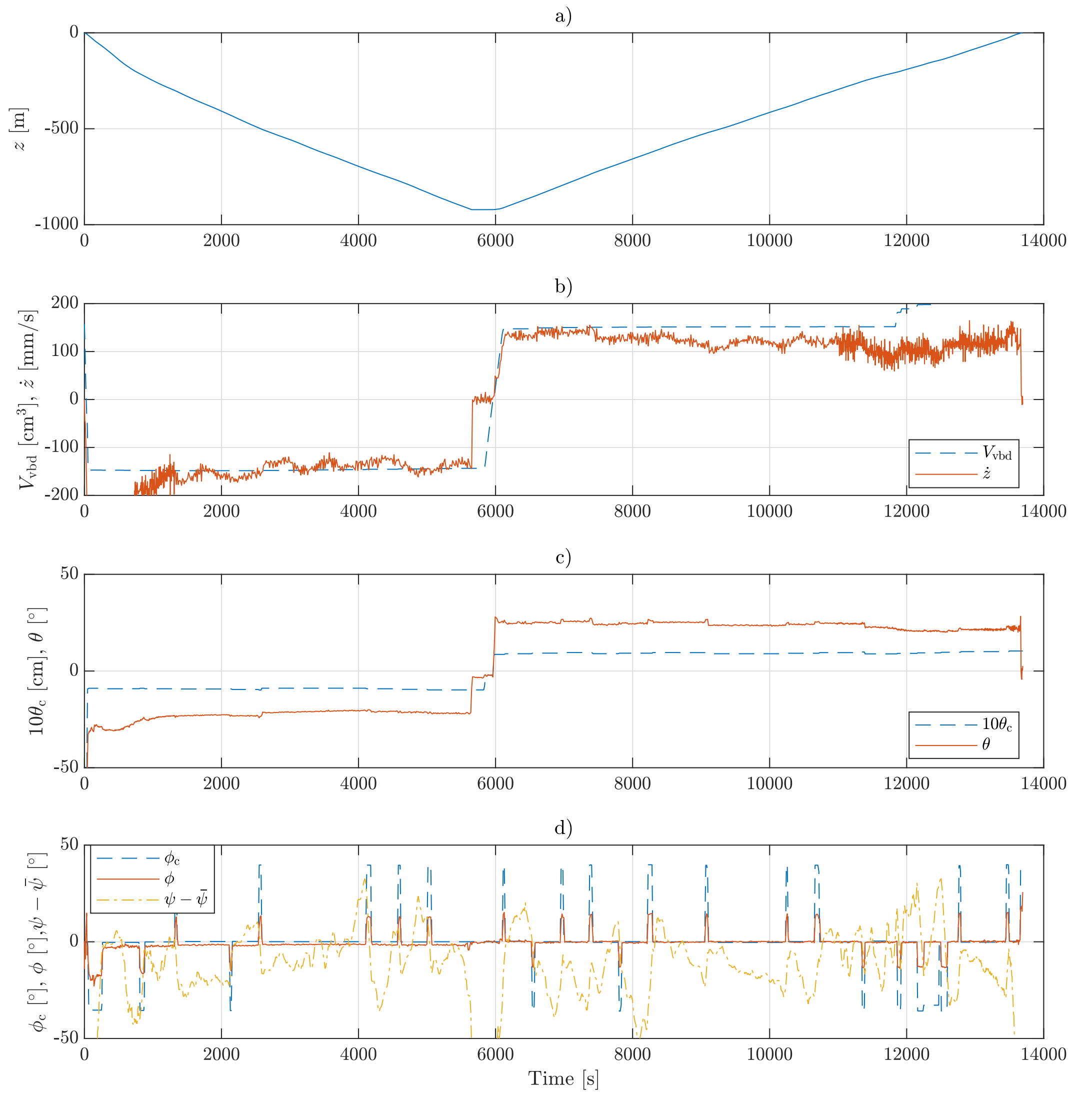
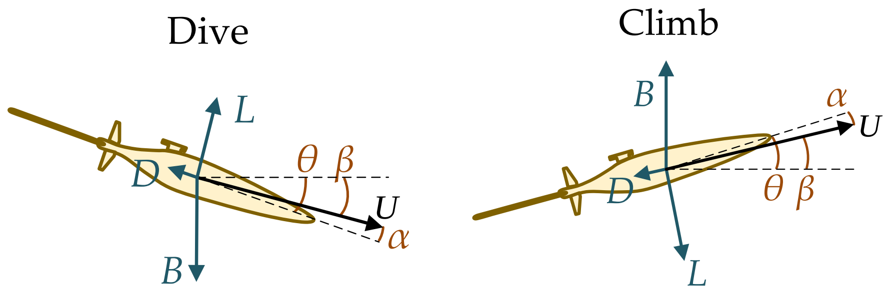


Figure 3: Example dive profile of an incorrectly trimmed glider.

$$L = al^2 q\alpha = -B\cos\beta, \tag{1a}$$

$$D = l^2 q\left(bq^{-0.25} + c\alpha^2\right) = B\sin\beta, \tag{1b}$$

where L [N] and D [N] are the lift and drag forces, respectively, l the length of the UG (1.8 m for Seagliders, ignoring the antenna) and a [deg^{-1}], b [N$^{0.25}$]



(a) (b)

Figure 4: Free-body diagram of the Seaglider in the vertical plane under steady-state conditions in a dive (a) and climb (b). B, D and L indicate the buoyancy, drag and lift forces, respectively, and α, β and *theta* the attack, glide and pitch angles, respectively.

and c [deg^{-2}] are the lift, drag and induced drag hydrodynamic coefficients, respectively. The units of the drag coefficient are due to the shape of the Seaglider, which ensures a laminar flow over the length of the UG up to the point when it tapers down into the antenna. As a result, drag scales with the speed in the water to the power of 1.5 instead of the typical 2 (Frajka-Williams et al., 2011). α [°] is the angle of attack and $\beta = \theta - \alpha$ [°] the glide slope angle. The dynamic pressure is $q = \rho(u^2 + w^2)/2$, where u [cm/s] and w [cm/s] are the horizontal and vertical velocity, respectively. The buoyancy force can be calculated as

$$B(t) = g\left[-m + \rho(t)\nabla(t, p, T)\right], \tag{2}$$

where m [g] is mass of the UG and $g = 9.81$ m/s^2 the gravitational acceleration. The volume displaced by the Seaglider is computed as

$$\nabla(t, p, T) = [V_0 + V_{\mathrm{vbd}}(t)] \exp\{-\gamma_{\mathrm{g}} p(t) + \alpha_{\mathrm{g}} [T(t) - T_0]\}, \tag{3}$$

where the reference temperature is set to $T_0 = 0$°C for simplicity (this means that degrees Celsius are used as unit instead of Kelvin - it is important to note that this does not correspond to the temperature at which the UG reference volume is taken), V_0 [cm^3] is the reference volume of the Seaglider, γ_{g} [dbar^{-1}] the absolute compressibility of the UG and α_{g} [1/°C] its thermal expansivity.

From (1a) and (1b), it is possible to obtain the following two equations for the dynamic pressure, q, and angle of attack, α, respectively,

$$q = \frac{B \sin \beta q^{0.25}}{2l^2 b} \left(1 + \sqrt{1 - \frac{4bc}{\alpha^2 \tan^2 \beta q^{0.25}}} \right), \tag{4a}$$

$$\alpha = -\frac{\alpha \tan \beta}{2c} \left(1 + \sqrt{1 - \frac{4bc}{\alpha^2 \tan^2 \beta q^{0.25}}} \right). \tag{4b}$$

Both (4a) and (4b) are implicit and thus require an iterative solution. Additionally, a check is needed to ensure the argument to the radical is positive; otherwise the data point will need to be discarded.

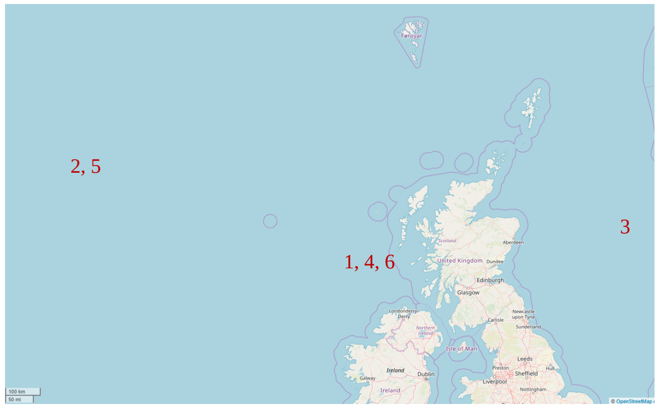
The vertical velocity predicted by the dynamic model, $\dot{z}_\mathrm{m}$, is therefore

$$\dot{z}_\mathrm{m} \approx w = \frac{2}{\rho} q \sin(\theta - \alpha) = \frac{2}{\rho} q \sin \beta. \tag{5}$$

Note that the vertical velocity must be then converted to [m/s].

2.3. Dataset

This study involved the analysis of the data measured by Seagliders during 12 missions. The Seagliders' deployments data have been taken from two main sources: the NOC and the Scottish Association for Marine Science (SAMS) in the UK (6 deployments) and the IMOS in Australia (6 deployments). Figure 5a and Figure 5b display the geographical position of the missions run by the NOC and IMOS, respectively. The Seaglider identity number, location, maximum target depth, mean surface temperature at the surface and number of dive cycles for the analysed deployments can be seen in Table 3. Whereas all missions present a maximum target depth close the rated depth of Seagliders (1000 m), the water temperature at the surface varies significantly with geographical location. This is expected to have consequences on the marine growth levels on Seagliders due to the UG's long missions, which each dive cycle lasting 4 to 8 hours. From Table 3, it is also possible to notice that the NOC typically operates the Seagliders for longer deployments.



(a)

(b)

Figure 5: Location of the Seagliders deployments run by the (a) NOC/SAMS and (b) IMOS used in the dataset.

3. Recommender System

In order to achieve symmetrical dive profiles for high quality scientific measurements and to reduce power consumption, it is important to determine the trim and flight parameters of the Seaglider. Currently, these parameters are obtained by pilots using the data collected during the UG's deployment

Table 3: Seaglider identity number, mission location, maximum target depth ($d_{\text{tgt,max}}$), mean temperature at the surface ($\overline{T_s}$) and number of dive cycles for all deployments in the analysed dataset. The mission duration is extracted from the GPS fix readings.

Dep. ID	Organisation	UG ID	Location	$d_{\text{tgt,max}}$ [m]	$\overline{T_s}$ [°C]	No. dive cycles	Mission duration [days]
1	NOC/SAMS	sg545	Hebrides	990	12.2	886	16.8
2	NOC/SAMS	sg532	North Atlantic	990	9.5	994	176.9
3	NOC/SAMS	sg550	North Sea	1000	10.3	1147	44.1
4	NOC	sg616	Hebrides	990	10.8	1667	165.9
5	NOC/SAMS	sg603	North Atlantic	990	10.2	1350	175.6
6	NOC/SAMS	sg602	Hebrides	990	12.6	1604	143.8
7	IMOS	sg153	Bremer Bay	990	19.8	268	33.7
8	IMOS	sg516	Brisbane	990	25.8	668	91.3
9	IMOS	sg514	Coral Sea	990	25.7	482	103.4
10	IMOS	sg516	Leeuwin	990	22.7	600	66.9
11	IMOS	sg540	Lizard Island	990	32.8	229	36.4
12	IMOS	sg514	Perth	990	21.0	699	107.9

based on manuals and procedures developed by the Seagliders developers (Eriksen et al., 2001; Frajka-Williams et al., 2011; IRobot, 2012). Here a recommender system is developed, which is designed to have a similar level of performance to expert pilots. Since the NOC is to implement the system on their UGs fleet control and command software soon, high robustness and a similarity to existing procedures are desired of the recommender system. For this reason, the existing strategies relying on steady-state conditions assumptions developed by Eriksen et al. (2001), Frajka-Williams et al. (2011) and IRobot (2012) have been adopted and improved upon.

3.1. Algorithm

The algorithm used for the recommender system of the trim and flight parameters of Seagliders is summarised in Figure 6. Furthermore, Figure 6 clearly delineates the different stages of the data preparation, parameters determination and update.

In an actual deployment, there is a time lag of two dive cycles in the update of the estimated trim and flight parameters due to the actual time required to process the data from the new run. Let us consider dive cycle i. After the dive cycle is completed, the data will be processed to obtain the new flight and trim parameters. However, the new parameters cannot be set for dive cycle $i + 1$, since the processing will take some time and when the Seaglider connects to the command and control software by satellite communication, it already requires new values. As a result, the update to the coefficients using the data from dive cycle i will be available only for dive cycle $i + 2$.

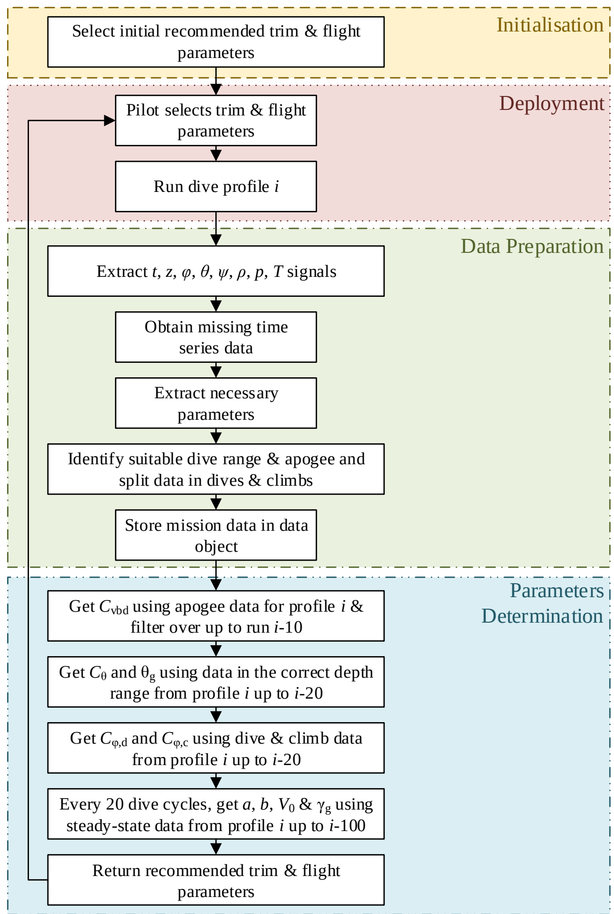


Figure 6: Workflow of the recommender system for the estimation of the trimming and flight parameters of Seagliders.

3.2. Trim Parameters

A UG needs to be trimmed correctly so that it can take scientific measurements at regular intervals in space and time on the desired path. The trimming operation consists in the correct zeroing of the pitch and roll control mechanisms and of the VBD by finding their respective actual centres, namely C_θ, $C_{\phi,\mathrm{d}}$, $C_{\phi,\mathrm{c}}$ and C_{vbd}, respectively (note that the roll control mechanism has a different centre for dives and climbs due to the top-bottom asymmetry of Seagliders because of appendages for scientific measurements). Based on pilots' observations, the values of the centres typically vary by approximately 15% for a Seaglider within a single mission and by up to 20% for different vehicles even for similar payload. Hence, their correct determination and the tracking of any changes are particularly important. Furthermore, the gain for the pitch control mechanism, θ_{g}, must also be estimated, which describes the change in pitch angle that corresponds to a linear displacement of 1 cm of the battery pack. The values of the centres are then converted into analogue/digital (A/D) units for the controller on board the Seaglider using appropriate conversion factors. This section describes how the centres of the VBD, pitch and roll control mechanisms are determined in the recommender system.

At the moment, a pilot determines the trim parameters during the first 10-20 dive profiles and subsequently updates them whenever necessary using software provided by the UG's manufacturer. Current practice dictates that the centres of the VBD and pitch control mechanisms should be determined first, since they have the strongest impact on the UG's trim and performance (IRobot, 2012). Subsequently, the roll control mechanism may be zeroed.

A similar approach is followed in the recommender system. Initially, the default values for C_{θ}, $C_{\phi,\mathrm{d}}$, $C_{\phi,\mathrm{c}}$ and C_{vbd}, which may be found in IRobot (2012), are returned. Then, the following methods are applied to estimate the actual trim parameters. The procedures are repeated throughout the glider deployments so that the parameters are constantly updated.

3.2.1. Determination of the VBD centre

After the Seaglider performs a dive profile, the position of the centre of the VBD is updated by analysing the difference in the zero-crossing time of the vertical velocity and VBD control signals as shown in Figure 2b. If the system were perfectly balanced, both signals would cross zero at the same time at the apogee, or lowest point, of the profile. If this is not the case, C_{vbd} is corrected by the magnitude of V_{vbd} at the time step when $\dot{z} = 0$. In the case of a well-calibrated system, e.g. as displayed in Figure 2, finding the point for which $\dot{z} = 0$ is relatively simple, despite the Seaglider collecting data points more frequently in the apogee region. Conversely, for incorrectly trimmed UGs, i.e. during the initial deployment stages, the glider may spend a long time changing from a downward to an upward glide, as can be seen in Figure 3. As a result, the point corresponding to the greatest depth is selected as the point for which $\dot{z} = 0$ occurs. With increasing number of dive cycles and hence updates to the estimate of C_{vbd}, this approach has been found to quickly lead to convergence to the expected VBD centre.

After analysing the deployments data, only 50% of the expected correction to C_{vbd} is applied as recommended by IRobot (2012) to pilots. The reason for this is the effect of the coupling of the VBD and pitch control centres on the UG's trim. Further filtering and activation functions are applied to reduce noise in the estimation of the centre of the VBD. Simple digital filters are used in this study, with different window sizes for the the various control mechanisms, as described in the appendix. The adjustments for the determination of the VBD centre are explained in detail in Appendix A.

3.2.2. Determination of the pitch centre and gain

To determine C_θ and θ_{g} the data corresponding to shallow depths and near the apogee are discarded. This means that only the data points corresponding to a vertical position in the following range are kept:

$$\min z + \min(|0.1 \min z|, 50 \text{ m}) < z < -\min(|0.1 \min z|, 50 \text{ m}). \qquad (6)$$

After one dive profile, the variation of the pitch angle with pitch control input is plotted as in Figure 7. Whereas in IRobot (2012) and Anderlini et al. (2019) the pitch control displacement in cm is considered, here the raw A/D values is used instead. This enables us to amalgamate data from a number of past dive cycles, thus speeding up convergence to the correct pitch centre and gain, even if the input C_θ and θ_{g} values are different. However, due to the effect of the coupling of the VBD and pitch control mechanism on the pitch angle of the Seaglider, only past data with the *same* C_{vbd} input may be accumulated as can be seen in Figure 7. The data are then fitted with a line, whose offset and slope can be used to determine the estimate of the pitch centre and gain. The slope yields θ_{g} after multiplication by the conversion factor from A/D to cm. The abscissa of the point where the line crosses $\theta = 0°$ corresponds to C_θ.

Like for C_{vbd}, accumulation, filtering and activation functions are used to reduce noise in the estimation of C_θ and θ_{g}. These are summarised in Appendix B.

3.2.3. Determination of the roll centres

The procedure to estimate the centres of the roll mechanism is similar to the one used to determine C_θ, with the variation of roll angle with roll control visible in Figure 8. However, the data is split into dive and climb, since Seagliders are top and bottom asymmetric. Additionally, similarly to the determination of the pitch centre, only the data points corresponding

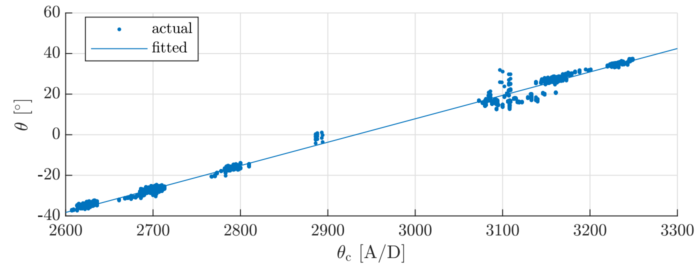


Figure 7: Variation of pitch angle with pitch control for an example dive profile.

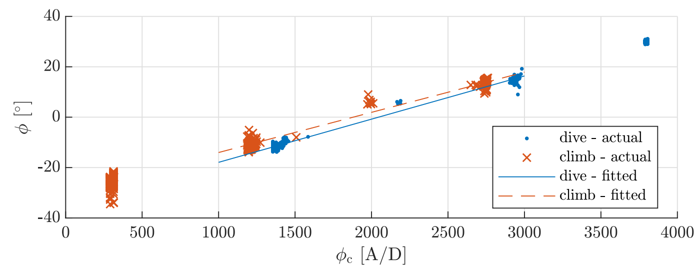


Figure 8: Variation of roll angle with roll control for the dive and climb (b) for an example dive profile.

to a vertical position described by (6) are kept. Furthermore, values corresponding to $\phi < 5°$ are ignored. This removes the cluster of points for $\phi \approx 0°$ corresponding to planar motions, but severely affected by disturbances due to ocean currents. Thus, ignoring the data points for $\phi < 5°$ greatly improves the quality of the linear fit to the roll data by focusing only on the rolling motions.

Similarly to C_θ, accumulation, filtering and activation functions are used to reduce noise in the estimation of $C_{\phi,\mathrm{d}}$ and $C_{\phi,\mathrm{c}}$. These are summarised in Appendix C.

3.3. Flight Parameters

In addition to the trim parameters, the pilots can also change some input parameters to the on-board flight model to optimise the Seaglider performance, which is based on the steady-state equations of motion (1-5). The main flight parameters with the respective initial values (Frajka-Williams et al., 2011) are

- hydrodynamic lift coefficient, $a = 0.003836$ deg^{-1},

- hydrodynamic drag coefficient, $b = 0.010078\ \mathrm{N}^{0.25}$,
- hydrodynamic induced drag coefficient, $c = 2.1 \times 10^6\ \mathrm{deg}^2$,
- glider absolute compressibility, $\gamma_\mathrm{g} = 4.4 \times 10^6\ \mathrm{dbar}^{-1}$,
- reference volume, $V_0 = m/\rho_0$ [cm^3], where ρ_0 is the reference water density [g/cm^3],
- glider thermal expansivity, $\alpha_\mathrm{g} = 7.05 \times 10^5\ ^\circ\mathrm{C}^{-1}$.

The reference density is set as the highest density experienced by the Seaglider and is also used to calculate the expected maximum buoyancy, B_max [g].

Eriksen et al. (2001) performed a regression analysis to determine a, b and c by minimising the difference of the UG vertical velocity with the one predicted by (5) from 100 dive profiles for a wide range of glide slopes. Similarly, Frajka-Williams et al. (2011) determined the hydrodynamic coefficients by combining the data from a whole deployment, although the principal aim of their study was the determination of vertical currents. Additionally, Frajka-Williams et al. (2011) assessed the sensitivity of the vertical velocity of a Seaglider with the flight parameters. Whereas the hydrodynamic lift and drag coefficients cause a change in the vertical velocity of different sign for climbs and dives, a positive change in the reference volume results in a negative change in the vertical velocity for both climbs and dives. Furthermore, although the impact of a, b and V_0 on $\dot{z}$ does not vary significantly with depth, the effect of the compressibility varies with depth because of the pressure (note that Seagliders are designed to have almost the same compressibility as water). The impact of c and α_g was found to be negligible. However, significant changes in the default value of the induced lift coefficient are possible if the Seaglider presents considerable appendages (Queste, 2018). In addition, the default values of a and b, which were obtained in wind tunnel experiments, are also known to vary due to the appendages (Eriksen et al., 2001). As a result, it is current standard practice at the NOC for pilots to run an optimisation to determine a, b, V_0 and γ_g after the first 50 dive cycles and subsequently updating them as more dive profiles are run by including the whole dataset. In particular, the optimisation for the pairs a and b and V_0 and γ_g are alternated, as done similarly by Queste (2018). Furthermore, $\dot{z}_\mathrm{m}$ and $\dot{z}$ are gridded in the $\theta - B$ search space to reduce the impact of salinity gradients (Frajka-Williams et al., 2011).

In order to ensure the robustness of the recommender system and ensure a speedy commissioning, the regression analysis on the steady-state model of the Seaglider is adopted. However, the development of a recommender system for the flight parameters presents a different objective from the study by Frajka-Williams et al. (2011), who tried to estimate vertical ocean currents, whose magnitude is of the order of 1-5 cm/s. Hence, the following modifications have been made:

- The flight parameters are first determined for the 100$^{\mathrm{th}}$ dive cycle and then recalculated every 20 dive cycles using data points accumulated over a number of past dive cycles. Analysing the data from all past dive cycles up to the current one as done by Eriksen et al. (2001) and Frajka-Williams et al. (2011) is undesirable, since changes in system dynamics would not be tracked. This is particularly important for condition monitoring of the UG, since the parameters can be used to identify changes in the system dynamics, e.g. due to marine growth or subsystem failures. Hence, the analysis of data coming from a moving window is preferred. Although Queste (2018) suggests 20 dive cycles could be an appropriate size for the moving window, this value has been found to be too small in this study. Here, the flight parameters are estimated using the data coming from up to 100 past dive cycles to ensure a sufficient number of data points are analysed to smooth out noise and dynamic effects. Finally, although here the flight parameters are updated only every 20 dive cycles due to computational constraints, considering the typical duration of 6-8 hours per dive cycle, it would be possible to compute an updated estimate after every dive cycle instead.

- Only a, b, V_0 and γ_{g} are estimated, although c is added to the optimisation for Seagliders with large sensory appendages.

- Instead of running two optimisations for the pairs a and b and V_0 and γ_{g}, a single optimisation is run for all parameters. This has been found to speed up and improve the quality of the optimisation due to sensitivity of the vertical speed to the different parameters.

- As opposed to Frajka-Williams et al. (2011) and Queste (2018), the values of the actual and predicted vertical velocity, i.e. $\dot{z}$ and $\dot{z}_{\mathrm{m}}$, respectively, are not gridded in the $\theta - B$ or $\theta - \dot{z}$ space. From the analysis of the data from the NOC and IMOS runs, gridding was found to increase the importance of data points on the edges of the data clusters around the $\theta \approx \pm 18°$-$\dot{z} \approx 0.15$ m/s regions, which are outliers and likely to be caused by dynamic effects that were not removed in the data cleaning process. The large number of data cycles analysed within the moving window ensures a sufficient number of points for both dives and climbs and reduces the impact of salinity gradients. Assuming the data is normally distributed, higher importance is given to the predictions in the operational range of the Seaglider during the mission.

- The cost function has been simplified to

$$J = \overline{|\dot{z} - \dot{z}_{\mathrm{m}}|}, \tag{7}$$

  where the bar indicates the mean excluding non-numerical values (nanmean in MATLAB). Excluding the non-numerical values is fundamental, since most grid points are non-numeric. Note also that the cost function includes points from both dives and climbs, thus resembling the one developed by Frajka-Williams et al. (2011).

- In order to ensure the steady-state, planar-motion assumption is met but at the same time maximise the number of data points available for the regression analysis, the time series data from the moving window of 100 dive cycles are cleaned. Firstly, all aborted runs or dive cycles where the Seaglider climbs tail-up are removed. Additionally, after taking some inspiration from Queste (2018), only the data points that meet the following requirements have been kept:

  - depth given by (6) to remove data points close to the surface or apogee, when nonlinearities are significant,
  - $|\dot{z}| > 0.02$ m/s to remove points when the UG has stalled,
  - $|\ddot{z}| < 0.01$ m/s^2 to avoid transient conditions,
  - $|\phi| < 2.5°$ to avoid roll angles and their associated coupled and nonlinear dynamic response,
  - $|\theta| < 45°$ to avoid excessive pitch angles,
  - $|\dot{\phi}| < 1°$/s to avoid transient conditions,
  - $|\dot{\theta}| < 1°$/s to avoid transient conditions.,

- p, T and ρ present numeric values.

Additionally, two points have been removed from each side of each segment of good data to further reduce the risk of inclusion of transient data.

- Finally, the flight parameters estimated every 20 dive cycles are further filtered over 5 values, which corresponds to 100 dive cycles. Furthermore, an activation function is applied, which ensures no change is applied unless

  - $\delta a > 0.001$ deg^{-1},
  - $\delta b > 0.001$ N$^{0.25}$,
  - $\delta c > 2 \times 10^{-6}$ deg^{-2},
  - $\delta < \gamma_{\mathrm{c}} > 2 \times 10^{-6}$ dbar^{-1},
  - $\delta V_0 > 10^3$ cm^3.

Whereas the default values are used for α_{g} and sometimes c, the recommender thus finds a, b, V_0 and γ_{g} (and c for Seagliders with large appendages) before each new dive profile by minimising (7) using the cleaned data from the past 100 dive cycles. The estimated vertical velocity values are obtained from (2-5), using iterative solutions for (4) up to 15 iteration or as soon as the change in estimated dynamic pressure is less than 0.001. The interior-point algorithm is used for the constrained optimisation using the MATLAB function *fmincon* with the following boundaries (Frajka-Williams et al., 2011):

- 0.001 deg$^{-1} < a < 0.007$ deg^{-1},
- 0.004 N$^{0.25} < b < 0.02$ N$^{0.25}$,
- 10^{-6} deg$^{-2} < c < 3 \times 10^{-5}$ deg^{-2},
- 10^{-6} dbar$^{-1} < \gamma_{\mathrm{c}} < 3 \times 10^{-5}$ dbar^{-1},
- $5 \times 10^4 < V_0 < 5.5 \times 10^4$ cm^3.

4. Results and Discussion

Figures 9-14 show the comparison of key trim and flight parameters estimated by the recommender system as compared with those actually selected by experienced pilots for the deployments run by the NOC and IMOS, which are representative of Seaglider missions in a broad range of oceanographic conditions.

From Figures 9-10, it is clear how closely the recommendations match the centres of the VBD and pitch control mechanism selected by the pilots. The same applies to the pitch gain, although it is not shown. The close comparison is expected, since only small improvements have been made over the system employed by the pilots to pick the three trim parameters. The activation and filter functions are successful in smoothing out excessive noise and preventing outliers (e.g. as shown by deployment 2, i.e. Seaglider 532 in the North Atlantic). However, the curve for the estimated pitch centre still presents some oscillations, particularly for deployment 10 (Seaglier 516 near Leeuwin). These oscillations are mainly due to convergence to local optima. The activation function should be improved to remove this undesirable outcome. The oscillations in the recommended value for the pitch value for Seagliders 602 and 603 in Figure 9 are interesting because they are not one-off errors. Hence, they are likely to be physical phenomena due to changes in the weight distribution or malfunctions of the glider towards the end of its deployment. These are reflected by changes in the roll centres in Figure 11 for the same dive profiles.

Conversely, the comparison between the roll centres selected by the recommender system and the pilots presents stronger differences as in Figures 11-12. The main reason for this behaviour is the removal of all points corresponding to $\phi < 5°$ in the recommender system, since they severely affect the quality of the linear fit. Hence, the recommender system is expected to be more precise. Additionally, outliers due to errors in the calculation of the slope and offset of the linear fit are no longer present.

For both the data selected by pilots and the recommender system, the values of the roll centres vary more significantly during a deployment as compared with the VBD and pitch control centres. This is likely caused by the lower amount of data the fit is based on and the impact of ocean currents, which have much higher horizontal than vertical magnitude (Rudnick, 2016). However, the sudden change in C_θ, $C_{\phi,\mathrm{d}}$ and $C_{\phi,\mathrm{c}}$ towards the end of a deployment may be caused by marine growth affecting the symmetry of the

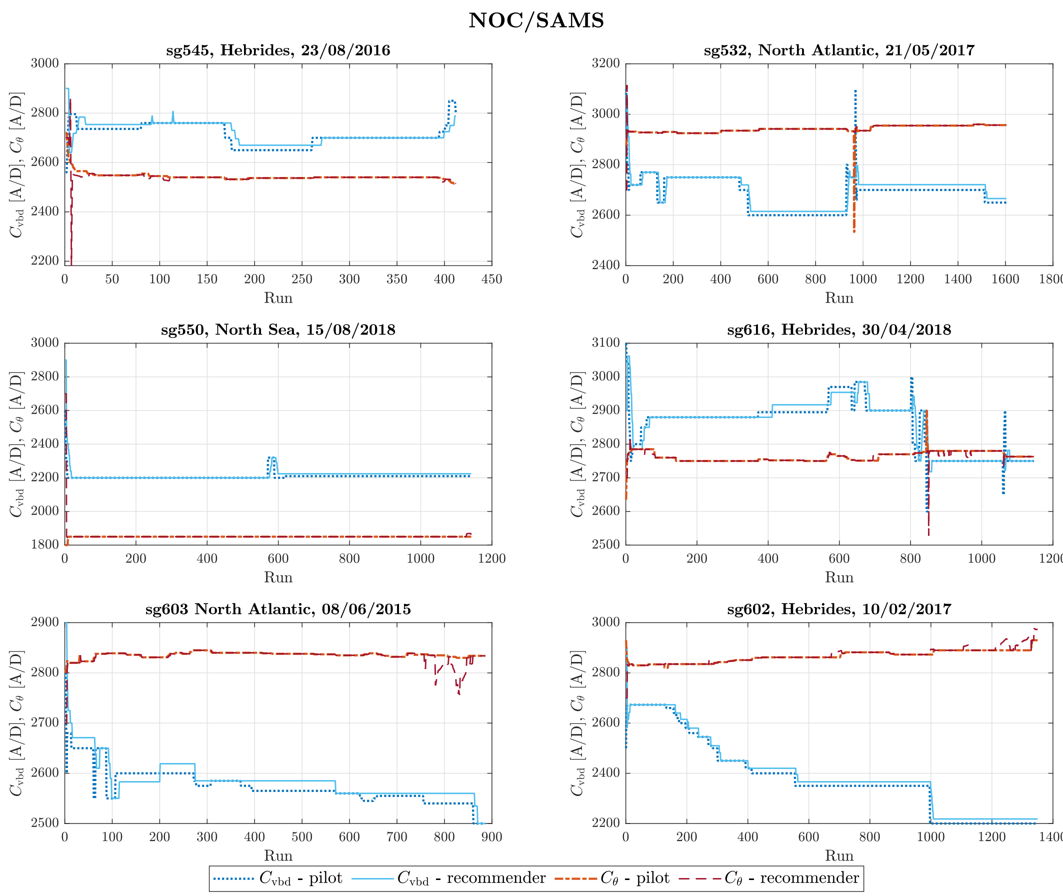


Figure 9: Variation of the centres of the VBD and pitch control mechanism with dive profile as selected by the pilots and recommended by the developed system for the missions run by the NOC/SAMS.

Seaglider, considering the long duration of the deployments.

From Figures 13-14, it is clear that the pilots did not attempt to change the hydrodynamic coefficients from the nominal values in any of the analysed deployments. For most missions, the recommender system presents values close to the nominal values. However, some oscillations can be observed, which are likely caused by the data sampling within the moving window. Hence, based on these results the operators will need to assess whether changing the flight parameters during a mission is desired or whether it is more appropriate to use fixed parameters, possibly determined from a previous deployment.

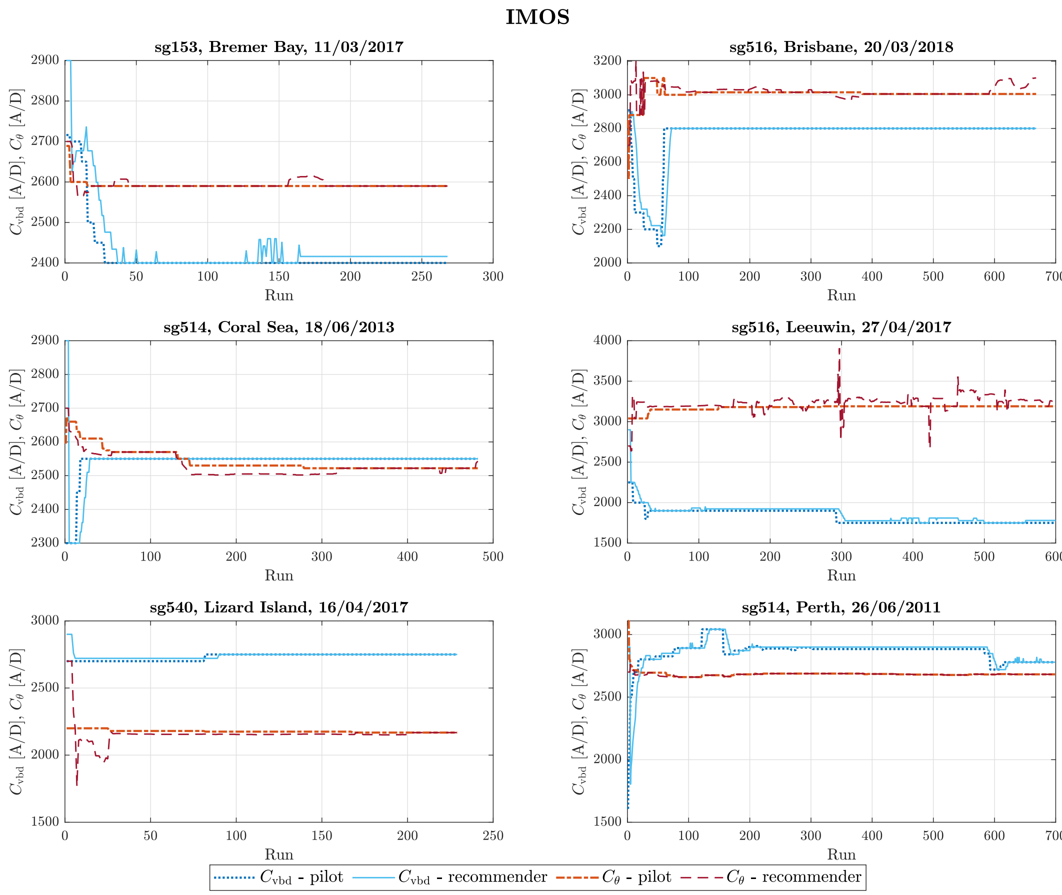


Figure 10: Variation of the centres of the VBD and pitch control mechanism with dive profile as selected by experienced pilots and recommended by the developed system for the missions run by the IMOS.

Nevertheless, as can be seen in Figures 13-14, deployments 4 and 8 (i.e. Seagliders 616 and 516 deployed near the Hebrides and Brisbane, respectively) show a steep increase in predicted drag coefficient towards the end of the mission. This is reflected in deployments 5 and 7 (i.e. Seagliders 603 and 153 in the North Atlantic and Bremer Bat, respectively) to a smaller degree. This phenomenon is likely to be physical and reflective of marine growth on the Seagliders increasing the resistance of their hulls. Hence, the hydrodynamic coefficients may also be used for the condition monitoring of the device (although the activation function is not necessary for that application).

The difference in the predicted and actually selected trim and flight pa-

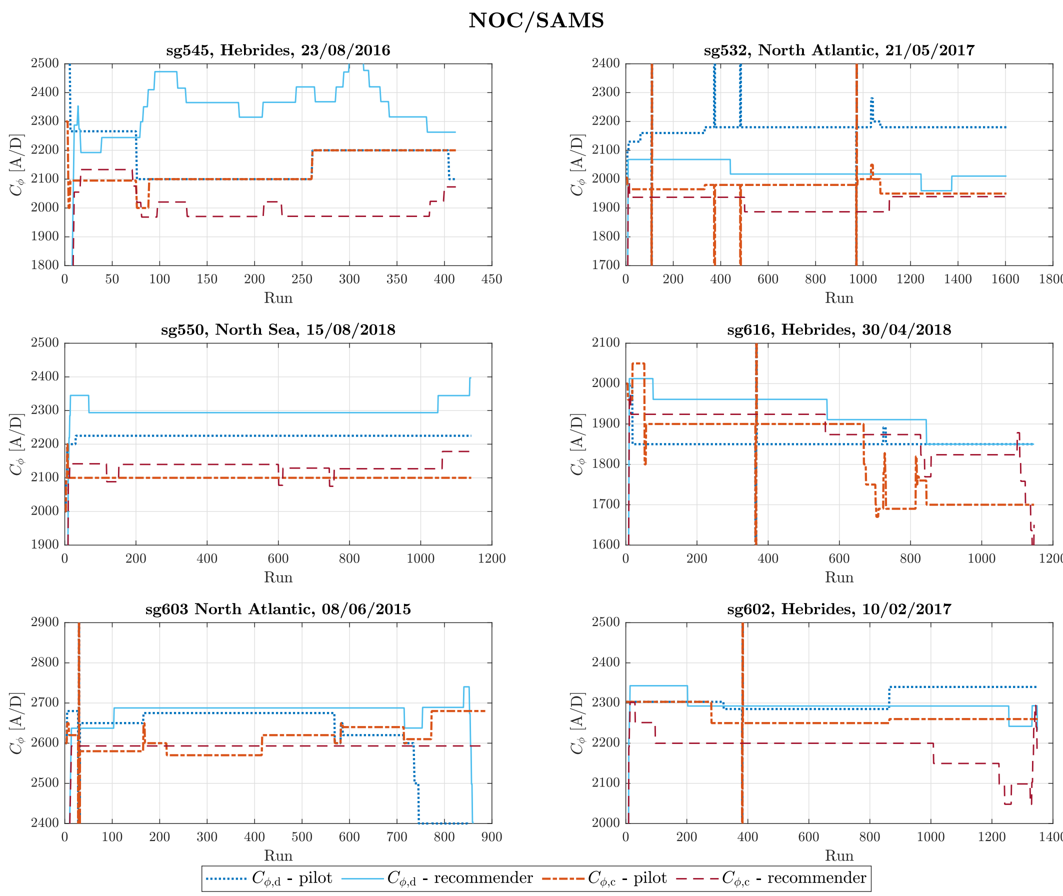


Figure 11: Variation of the centres of the roll control mechanism for dives and climbs with dive profile as selected by experienced pilots and recommended by the developed system for the missions run by the NOC/SAMS.

rameters is quantified in Tables 4-5, which display the ratio of the mean absolute difference and the respective nominal values and the ratio of the standard deviation of the absolute difference and the corresponding nominal values, respectively. The tables reflect the trends shown by Figures 9-14. From Table 4, it is clear that there is excellent agreement between the values selected by the pilots and the recommender system. However, the estimation of the roll centres and hydrodynamic coefficients present a mean absolute percentage difference, which is one to two orders of magnitude greater than the centres of the VBD and pitch control mechanisms due to the significant changes in the procedure used for the data cleaning, linear fit and cost

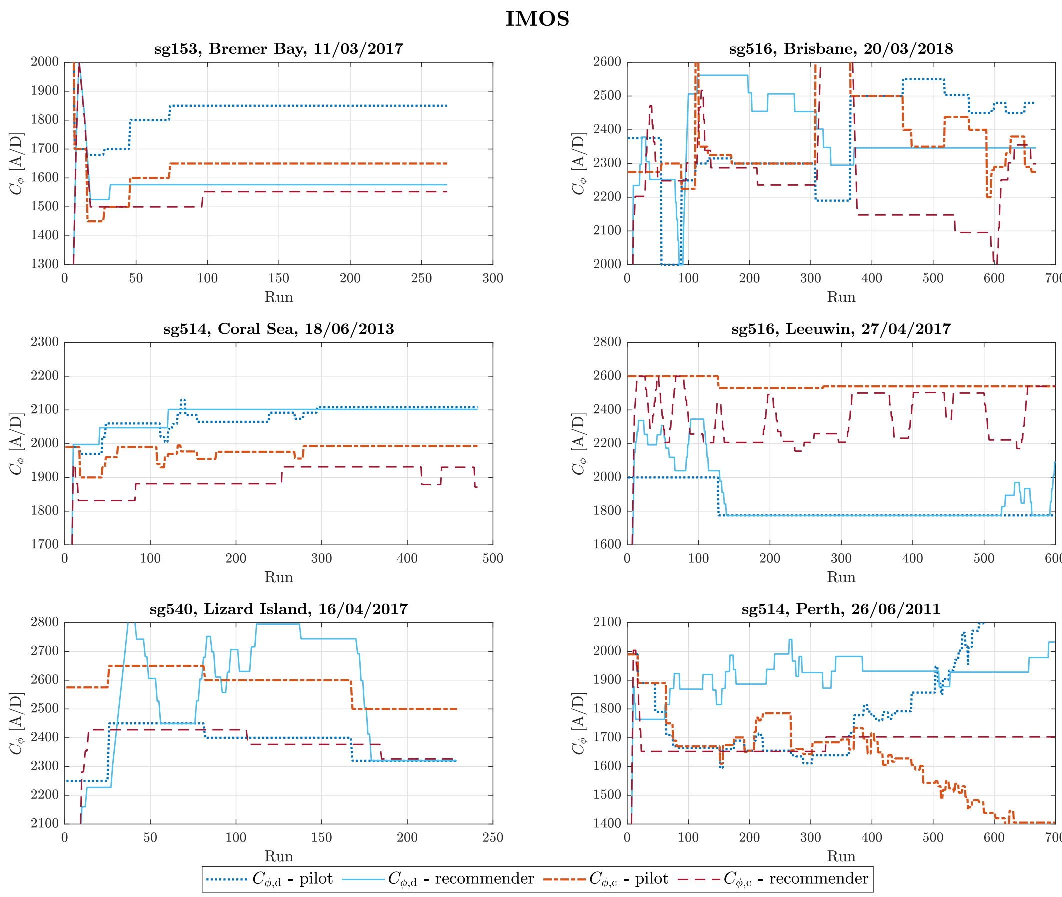


Figure 12: Variation of the centres of the roll control mechanism for dives and climbs with dive profile as selected by experienced pilots and recommended by the developed system for the missions run by the IMOS.

function. From Table 5, the standard deviation is more representative of the visual differences shown in Figures 9-14, since it accounts for changes in the selected trim and flight parameters with dive cycles. However, Table 5 reflects the trend of Table 4 for the individual parameters.

4.1. Suggestions for Operational Practice

After the development of the recommender system, the authors would like to summarise a number of practices that can help with the operation of Seagliders, particularly for large oceanographic centres.

Firstly, the creation of a database for the trim and flight parameters for

Table 4: Mean absolute difference between the prediction of the recommender system and the respective values selected by the pilots divided by the nominal value for the trim and flight parameters.

ID	VBD [%]	θ [%]	ϕ_{d} [%]	ϕ_{c} [%]	a [%]	b [%]
1	0.597	0.150	11.163	7.828	5.677	0.000
2	0.619	0.053	8.114	3.178	38.261	8.349
3	0.409	0.131	4.124	2.216	46.335	8.059
4	0.518	0.067	4.066	4.056	33.761	40.384
5	0.569	0.121	4.241	2.725	29.364	16.153
6	0.572	0.180	2.008	4.357	25.384	4.942
7	0.748	0.161	13.689	6.344	26.598	3.833
8	0.605	0.830	9.113	7.697	35.748	34.429
9	0.313	0.496	1.739	4.885	19.099	0.000
10	1.169	2.922	3.310	10.248	6.117	2.336
11	0.405	1.425	10.749	12.167	0.000	3.074
12	1.085	0.124	10.829	6.524	19.197	0.810
mean	0.634	0.555	6.929	6.019	23.795	10.197

Table 5: Standard deviation of the absolute difference between the prediction of the recommender system and the respective values selected by the pilots divided by the nominal value for the trim and flight parameters.

ID	VBD [%]	θ [%]	ϕ_{d} [%]	ϕ_{c} [%]	a [%]	b [%]
1	1.187	0.933	12.503	9.096	10.991	0.000
2	0.907	0.680	7.302	7.527	22.131	4.738
3	1.212	1.973	4.890	5.006	22.938	4.890
4	1.177	0.387	6.781	6.900	25.135	41.770
5	0.653	0.443	10.751	9.888	22.500	13.398
6	0.692	0.545	6.457	6.439	21.766	4.545
7	1.324	0.424	10.070	10.987	26.610	7.298
8	2.577	1.481	7.799	9.446	24.649	40.624
9	2.058	0.543	7.380	7.123	15.654	0.000
10	2.118	2.724	8.042	11.049	11.499	4.805
11	0.948	2.941	13.681	13.818	0.000	5.311
12	3.243	0.862	7.181	7.578	19.124	3.337
mean	1.508	1.161	8.570	8.738	18.583	10.893

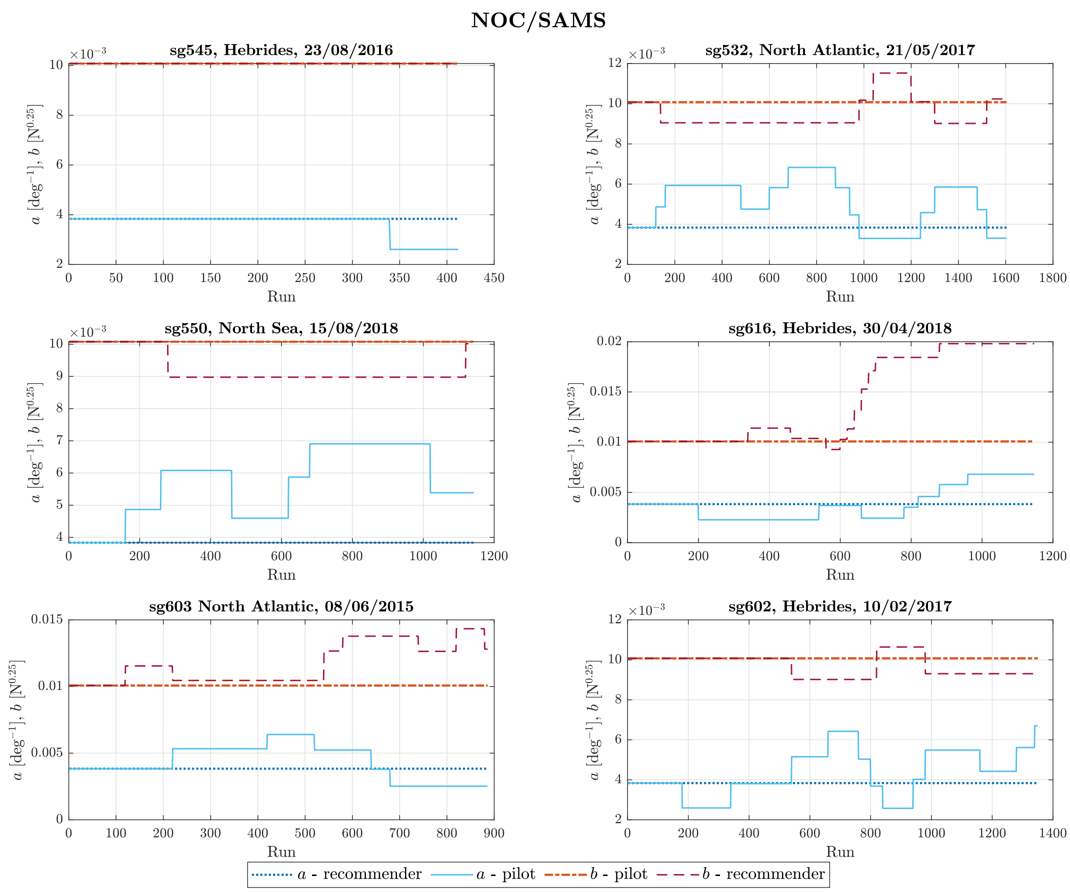


Figure 13: Variation of the lift and drag coefficients with dive profile as selected by the pilots and recommended by the developed system for the missions run by the NOC/SAMS.

individual Seagliders and configurations (i.e. the sensors or payloads they carry) is highly recommended. This would greatly improve the speed and ease of the initial trimming of the UG. Additionally, the database would provide a more reliable start point for the recommender system, which would still be used to track changes in the trim and flight parameters. For instance, the pressure hull compressibility may change with time. Data on the UGs' configurations may be used to aid the determination of the trim and flight parameters for newly commissioned gliders.

Secondly, the reference volume may be determined at the surface either on the mother ship or the facility just before a deployment. This procedure is standard practice at most oceanographic institutions, like the NOC. This

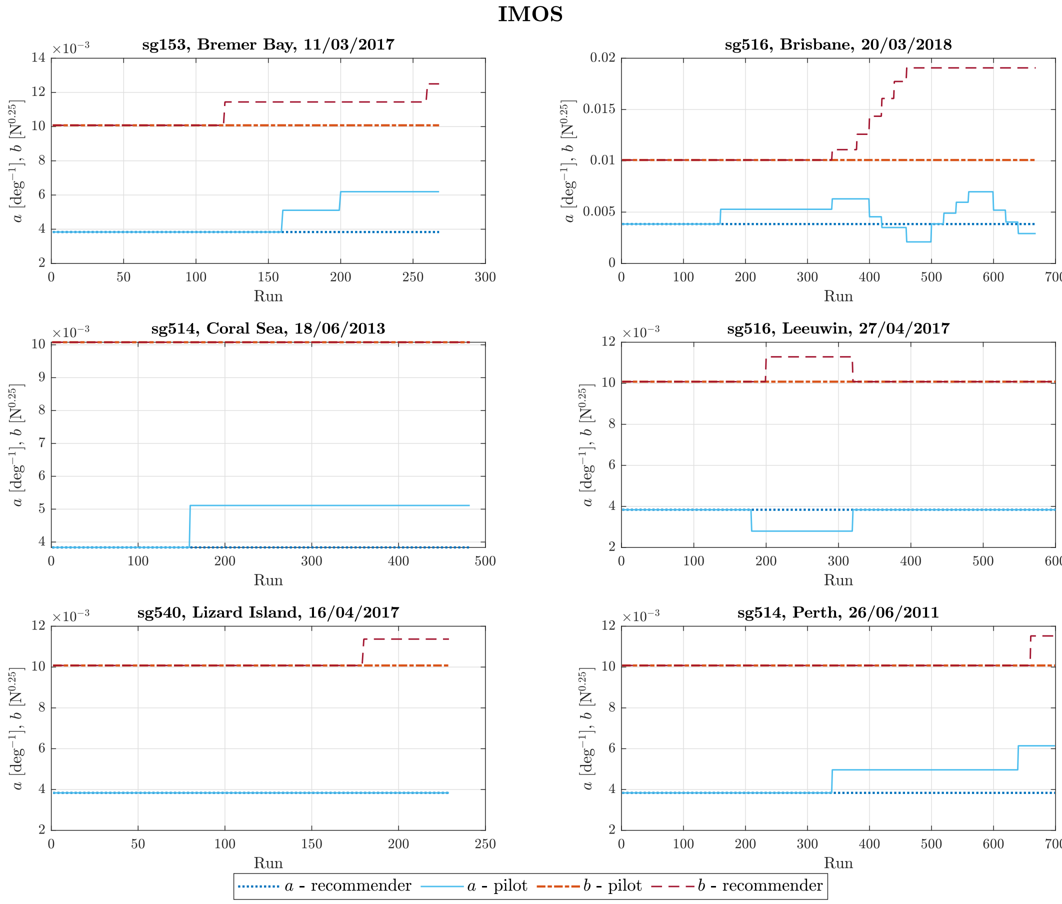


Figure 14: Variation of the lift and drag coefficients with dive profile as selected by the pilots and recommended by the developed system for the missions run by the IMOS.

task can be performed in a tank of appropriate size and constant cross-section filled with seawater, with readings being taken on at least four sides to average out oscillations (e.g. due to waves). Additionally, from this process T_0, i.e. the reference temperature, may be determined. Measuring V_0 before the deployment would provide higher accuracy than the regression analysis explained in this article and it would improve the accuracy and computational speed of the estimation of the hydrodynamic coefficients and compressibility of the Seaglider by fixing one of the four (or five) flight parameters.

The amount of marine growth observed at the end of a deployment should be quantified and stored in a database so that it may be used to determine whether tracking the hydrodynamic coefficients may be used for remote condition monitoring of the Seaglider.

Finally, dive cycles for close to the maximum target depth for the mission should be performed sooner so that the trimming operation may be completed more accurately and faster. However, care needs to be ensured a sufficiently large maximum buoyancy value is allowed at the start so as to ensure the UG will climb to the surface in the worst case scenario before trimming is completed (IRobot, 2012).

5. Conclusions

An effective recommender system for the trim and flight parameters of Seagliders has been developed to aid trainee pilots and facilitate round-the-clock operations. Although the system presents improvements over standard practices, it relies on the self-same assumption of steady-state flight conditions and resulting equations of motion at equilibrium to increase its robustness and speed up its implementation. Additionally, suggestions are made for oceanographic centres to reap the benefits from the operation of large fleets of gliders.

The performance of the recommender system has been assessed against the selection of the trim and flight parameters of Seagliders by expert pilots for 12 deployments run by the NOC and IMOS. While the VBD and pitch centres present a very close comparison, greater difference is shown by the roll centres. This is due to removal of the points corresponding to zero roll angle in the recommender system from the linear fit of roll angle with roll control input, since they only contribute to noise. The predicted lift and drag coefficients are also similar to the nominal values, which are selected by the pilots in all analysed deployments. However, for four missions, an increase in drag towards the end of the deployment is likely to be representative of marine growth on the Seaglider. As a result, tracking the hydrodynamic coefficients may be investigated as a tool for the condition monitoring of Seagliders.

The recommender system will now be implemented in the command and control cloud software of the NOC. Due to its high performance, the developed system is expected to greatly help trainee Seaglider pilots achieve a comparable level of expertise to professional pilots from the very beginning. After extensive testing, the system is also anticipated to provide a level of autonomy to gliders' operations during night hours.

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Appendix A. Determination of the VBD Centre

The following further adjustments have been made to reduce the noise in the estimation of the VBD centre:

- No change is made to C_{vbd} if the dive profile is aborted or if the glider climbs tail up and nose down.
- An activation function is included so that no change is made if $\delta C_{\mathrm{vbd}} <$ 15 A/D or $\delta C_{\mathrm{vbd}} >$ 999 A/D, where δC_{vbd} defines the estimated change in VBD centre over the value used as input during the dive.
- The value of C_{vbd} is averaged over up to 10 past dive profiles or up to as many past dive profiles with the same C_{vbd} as the current one, whichever is smallest. This adjustment is particularly important to filter inaccuracies in the determination of the apogee, e.g. as shown in Figure 3.
- A further activation is applied so that no change is made unless $\delta C_{\mathrm{vbd}} \geq$ 25 A/D.
- The value of C_{vbd} is clipped to the maximum and minimum values specified in the manual (IRobot, 2012) so as to prevent the VBD from hitting the end stops.

Appendix B. Determination of the Pitch Centre and Gain

The following adjustments have been made to reduce the noise in the estimation of the centre and gain of the pitch control mechanism:

- No change is made if the dive profile is aborted or if the glider climbs tail up and nose down.

- There is no need to correct for 50% of the expected change in pitch centre and gain, since data from multiple dive profiles is analysed and the absolute value of the pitch centre is determined rather than relative changes.

- The gain of the pitch control mechanism is not corrected unless the centre is too.

- The pitch angle and pitch raw control data are accumulated for up to 20 past profiles or up to as many past dive profiles with the same centre of the VBD as the current one, whichever is smallest. Only the data corresponding to an angle of roll $|\phi| < 5°$ is kept to avoid coupled dynamic effects, as identified as a problem by Frajka-Williams et al. (2011). This process is particularly important to smooth out sensor noise.

- No change is made if $\delta C_\theta < 15$ A/D or $\delta C_\theta > 999$ A/D to remove the effect of numerical errors in the linear fit.

- The estimate of the pitch gain is filtered over the past 10 values. Furthermore, outliers are removed from the pitch gain prediction.

- The values of the pitch control centre and gain are clipped to the maximum and minimum values specified in the manual (IRobot, 2012) so as to prevent the battery pack from hitting the end stops.

Appendix C. Determination of the Roll Centres

The following adjustments have been made to reduce noise in the estimation of the centres of the roll control mechanism:

- No change is made if the dive profile is aborted or if the glider climbs tail up and nose down.

- $C_{\phi,\mathrm{d}}$ and $C_{\phi,\mathrm{c}}$ are corrected independently of each other.

- There is no need to correct for 50% of the expected change in roll centre, since data from multiple dive profiles is analysed and the absolute value of the roll centre is determined rather than relative changes.

- The roll angle and control data are accumulated for up to 20 past profiles or up to as many past dive profiles with the same $C_{\phi,\mathrm{d}}$ or $C_{\phi,\mathrm{c}}$ as the current one, whichever is smallest. This process is particularly important to smooth out sensor noise.

- No change is made if $\delta C_\phi < 15$ A/D or $\delta C_\phi > 399$ A/D.

- The estimate of the roll centre is filtered over the past 10 values. Furthermore, a further activation function is applied so that no change is applied unless $\delta C_\phi > 49$ A/D to prevent many changes in roll centre, which have found to be a problem in current practice.

- The values of the roll centres are clipped to the maximum and minimum values specified in the manual (IRobot, 2012) so as to prevent the Seaglider from capsizing.

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