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A 2D model for the study of equilibrium glide paths of UiS Subsea Freight-Glider

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A 2D model for the study of equilibrium glide paths of UiS Subsea Freight-Glider

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Abstract. A planar mathematical model for the analysis of equilibrium glide paths of the UiS subsea freight-glider (USFG) is presented. The model is developed using Simscape Multibody in MATLAB/Simulink to study the ever-changing dynamics of the glider. Motion along the heave and pitch direction is regulated by two separate PID controllers. Controllers are tuned for the optimal bandwidth and phase margin to provide the system with ideal gains which satisfy the system requirements. A wide-ranging sensitivity investigation is carried out on the USFG by changing the two key variables, pump flow rate and ballast fraction. The results reflect the advantages of using higher flow capacity and ballast fraction, which should be preferred according to the application, provided if there are no space and weight restrictions. Finally, different glide paths were simulated to observe that, controller gains obtained from the linear model can be improved to acquire better performance in terms of robustness and stability of the system.

1. Introduction

The subsea glider concept is fascinating owing to its efficient propulsion system. Envisaged by Stommel [1] in 1989, subsea gliders have come a long way from a concept to a real-world technology used for various purposes. This concept is utilized in Autonomous Underwater Vehicles (AUVs) which are employed to amass ocean data. They are usually deployed for numerous months during operation, covering hundreds of miles without any provision ships. Extensive research has been carried out on the design and control of underwater gliders, some examples include the DOF [2] and AUVAC subsea gliders [3]. Nevertheless, due to their limited size and load carrying capacity, these AUVs have not been utilized much for cargo transportation. To the author's knowledge, there has been only one cargo-carrying AUV so far which is developed by ISE Ltd, for the Spinnaker program in the 1990s [4]. Theseus was developed for cable-laying missions in the arctic to carry a payload of 660 kg over the range of 900 km. Further, equinor also suggested utilizing large subsea gliders for conveying freight [5]. However, this was just a proposal of concept without many technical details considered.

University of Stavanger Subsea Freight-Glider (USFG) as seen in Figure 1, was recently proposed by Xing [6] to utilize the ultra-efficient subsea glider principle for cargo transport. The main design parameters are listed in Table 1. As illustrated in Figure 2, it thrusts itself onwards following a sawtooth motion. In the upward cycle, it pumps out the ballast water such that the buoyancy force becomes positive and carries the glider to the desired operating depth. In the opposite direction, it will pump in ballast water and the vehicle gains weight. As a result, the buoyancy force becomes negative which lets the glider dive to its initial depth. The hydrodynamic wings generate lift and drag forces as the freight-glider cycles up and down, thereby propelling the vessel forward in the water. This entire process is repeated throughout the entire journey. This propulsion method uses energy only for regulating the ballast water between the tanks, while propulsion is indirectly created by the wings. In doing so, it consumes minimal energy while carrying a huge quantity of payload. The USFG is aimed as an ultra-low-energy substitute to prevailing solutions as such pipelines, tanker ships, and bulk carriers. With its highly efficient propulsion, it can contribute to the reduction of ocean transport-related emissions (about 3 % of global carbon emissions) [7].

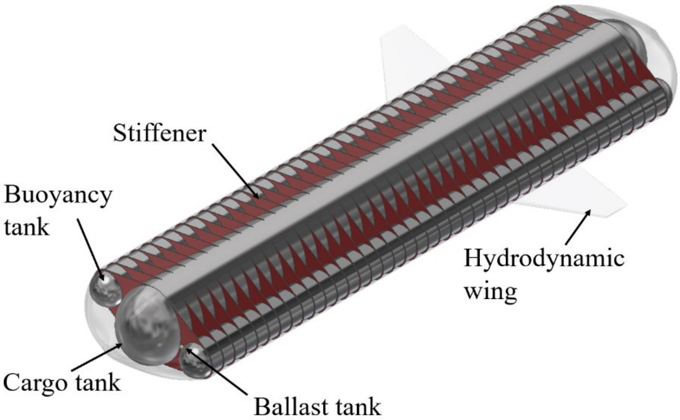


Figure 1. UiS Subsea Freight-Glider.

Table 1. Design parameters of UiS Subsea Freight-glider.

Parameter	Value	Unit
Vessel length	50	m
Cargo tank diameter	5.0	m
Buoyancy tank diameter	2.2	m
Deadweight ton	1533	ton
Structural weight	470	ton
Cargo weight	785	ton
Ballast fraction	0.15	%
Diving depth	200	m
Glide path angle	38	°
Wing area	20	m^2
Volumetric drag coefficient	0.1	-
Ballast pump capacity	2000	m^3/h
Pumping time / cycle	< 5% of half cycle	-
Horizontal speed	1	m/s
Average Power	< 10	KW
Net transport economy	< 0.5	-

Owing to its considerable size, controlling pre-programmed ballasting and de-ballasting system, which is being utilized in a massive, submerged structure is a technical problem requiring further investigations. Furthermore, due to the limitations imposed by environmental conditions, the glider faces two challenges: (a) lower maneuverability and (b) longer response time to control pitching angles and elevation. Therefore, a stable and robust control system is required to tackle any sort of variations experienced by the vessel.

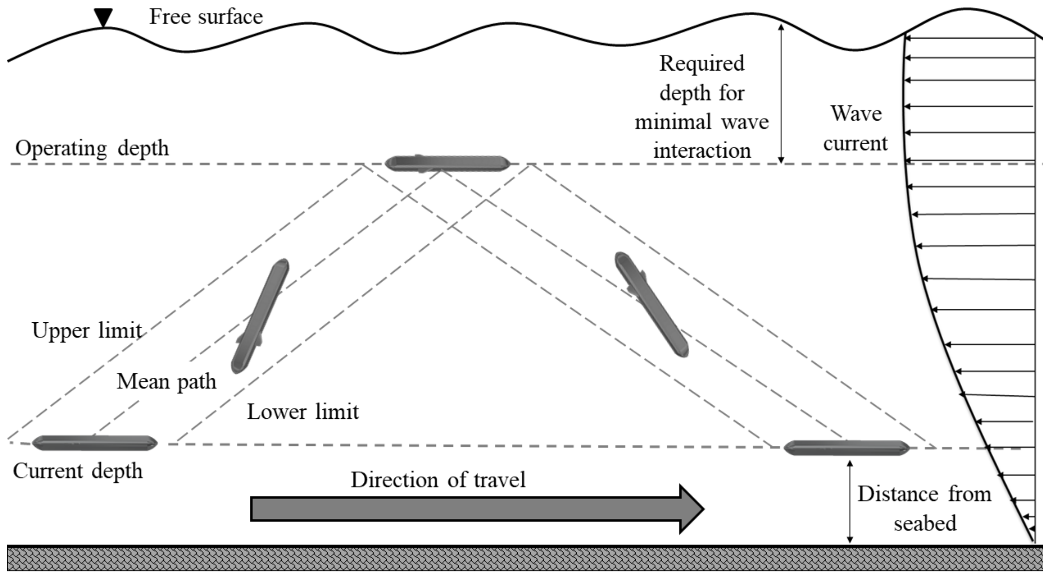


Figure 2. Equilibrium glide paths.

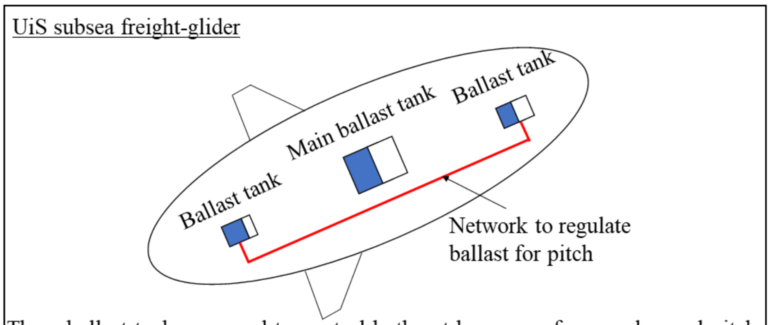
Previously, a significant amount of work has been done to scrutinize the three vital pillars or features of underwater vehicles: cargo or freight-carrying capability by LSE Ltd [4], autonomous or self-directing ability by Fossen [8] and equilibrium glides by Graver [9]. This paper combines these critical domains to study the equilibrium gliding paths for an autonomous underwater vehicle capable of carrying 785 metric tons as highlighted in Table 1.

This paper concerns modeling the dynamics of the USFG to analyze the control system for ballasting and flight path. The aim is to develop a dynamic model to cater for buoyancy and hydrodynamic forces to investigate the equilibrium glides for USFG, which involves the sawtooth gliding path in a 2D plane. While carrying cargo the USFG has to take a pre-planned path to maximize its travel range as illustrated in Figure 2. The ability to navigate accurately is quite critical when it comes to the design of the underwater glider. Maintaining the desired path can likely aid in energy conservation since we do not want to exceed the one-fourth part of the pre-determined energy budget as studied by Langebrake [10]. For this purpose, the glider must keep itself within the range of the planned path and avoid any deviations, since position tracking is only performed during the initial stages for autonomous vehicles as highlighted by Gwyn et al. [11]. After the system is modeled, a few vital studies including, controller tuning and sensitivity analysis, are carried out. This allows the author to further augment the performance of the mathematical model for the performance of the USFG. Finally, various glide paths are simulated against the base case to investigate different operating conditions. This is done to study the importance of optimal controller gains for the desired response.

2. Ballasting system

Normally in an ordinary AUV, the net buoyancy force is regulated by altering the ballast volume, whereas motion in the direction of pitch and roll is adjusted by regulating the center of mass with the aid of a mass actuator. This method cannot be applied to enormous freight-carrying gliders such as the USFG. The mass that needs to be actuated is considerably heavy and the conventional techniques would require a substantial hydraulic network. Moreover, when it comes to the control of glider dynamics a quick response system is needed to efficiently tackle any changes, i.e., a sluggish response system is not desired. To achieve good response times, USFG exploits a coalescence of ballast tanks for gliding and ailerons for control of motions like pitch and roll as illustrated in Figure 3.

The ballast system for heave and pitch motion is controlled by two separate proportional-integral-derivative (PID) controllers. Controller gains are adjusted with the aid of the PID tuner in Simulink. Moreover, the extended details concerning the model and the tuning of these controllers are discussed in the upcoming sections. The scope of this work is limited to a two-dimensional problem but, it can be easily expanded to a three-dimensional model. Figure 3 shows the ballast system used to control the heave and pitch motion of the glider. Motion along the heave direction is varied by the large buoyancy tank located at the center of gravity (COG) of the vessel, which controls water with the aid of a pump onboard. Desired pitch angles are attained by pumping water in and out of the two secondary ballast tanks simultaneously. It must be noted that these tanks are connected to form a network as indicated in Figure 3.



Three ballast tanks are used to control both net buoyancy force and vessel pitch angle. In this case, the ballast tank at the stern has more water compared to the one at the bow. The secondary ballast tanks at the fore and aft of the glider are connected in a closed network. Ballast mass is regulated amongst these tanks to obtain desired pitch.

Figure 3. The control scheme of the UiS subsea freight-glider.

3. Simulink/Simscape implementation

A mathematical model of the UiS subsea freight-glider has been developed in MATLAB Simscape Multibody also referred to as SimMechanics. The Simscape model is depicted in Figure 4.

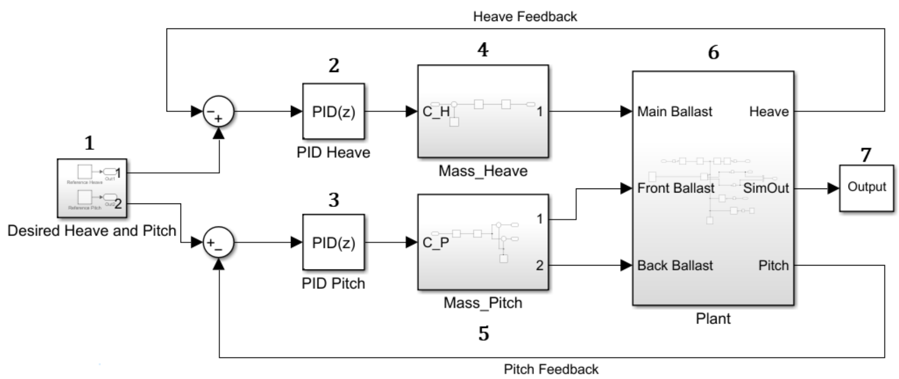


Figure 4. Simscape dynamic model.

The Simscape model for the UiS subsea glider consists of the subsequent key parts as characterized in Figure 4.

- Sub-system 1: Delivers required values for heave and pitch angles provided by the pilot.
- Sub-system 2: PID controller for heave response.

- Sub-system 3: Pitch motion PID controller, it must be noted that; independent controllers are used for actuation of the glider for pitch and heave motion.
- Sub-system 4: Manages the main ballast tank mass which controls the up and down motion of the glider. It also encompasses saturation (*bounds the ballast value*) for the main ballast tank and rate limiter (*limits the pump flow rate*).
- Sub-system 5: Fluctuates the ballast mass between two secondary tanks, i.e., Front and Back ballast tanks, it does so to control the pitch angles of the glider. It comprises the rate limiter (*controls mass being pumped in or out of the secondary tanks*) and as well as the saturation block (*confines the secondary tank capacity).*
- Sub-system 6: Termed as plant block in Figure 4, it represents the two-dimensional dynamic model of the UiS subsea freight-glider.
- Sub-system 7: Prompts and stores the results to MATLAB workspace for post-processing.

It must be noted that a control state is programmed to control the motion of the vessel during gliding in the sawtooth path. It is implemented in such a way that, when the value of the state is returned as “1” the USFG is programmed to glide upwards to the required elevation while moving forward. Similarly, when the value is “-1” it glides downwards to the initial depth.

3.1. Plant model

The plant model (represented by block 6 in Figure 4) is fully described in the upcoming text, Figure 5 presents a systematic view of the entire plant block.

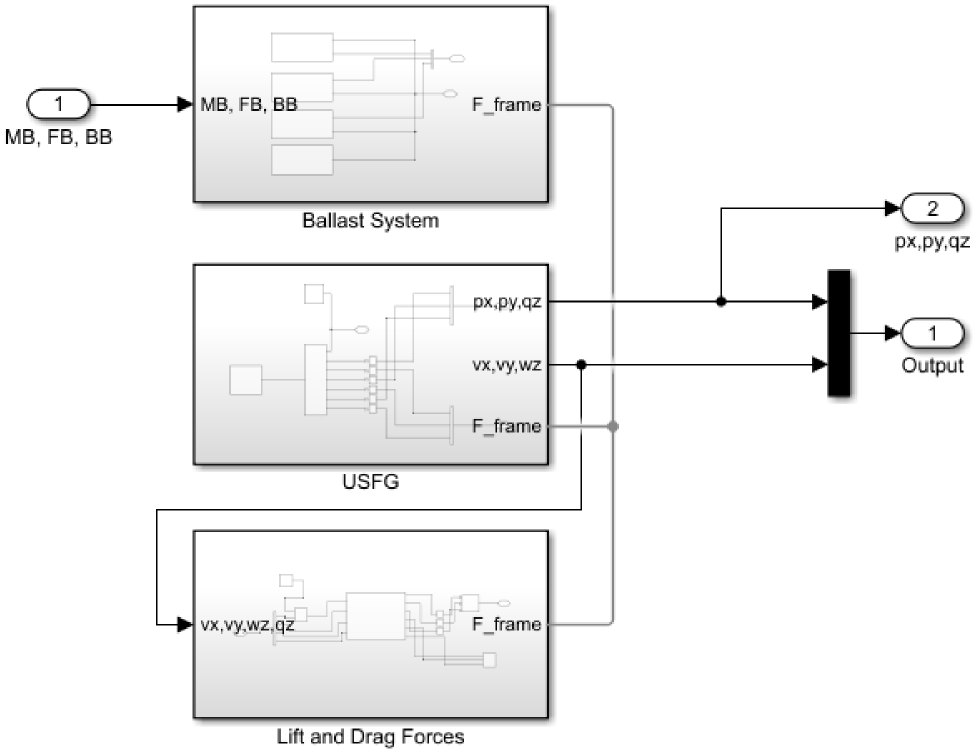


Figure 5. Plant model.

The following three main blocks are represented for the plant model:

- Ballast system: This block is used to model the dynamics of the ballast system in USFG. It takes in the control inputs for ballasts (Main, Front, and Back) and delivers them as an input for forces to the USFG block. Furthermore, it also provides the glider with the buoyancy force.

- USFG: Contains a two-dimensional rigid body having three degrees of freedom in *x, y*, and *z* directions. Equations of motion will be solved in this block by Simulink based on the forces implemented on the body.
- Lift and drag forces: Based on the angle of attack of the incoming flow, lift, drag, and rotational torque are calculated by taking into account the velocity of the USFG along with pitch angles. These forces then serve as an input to the USFG block. The lift and drag coefficients are a function of angle of attack (α) and are calculated using the equations (1) and (2):

$$C_L = 5\alpha^2 + 10\alpha \tag{1}$$

$$C_D = 0.4\alpha^2 + \alpha + 0.1 \tag{2}$$

4. Control theory and controller tuning

As stated previously, this work will limit its scope to a 2D dynamic problem for the UiS glider, i.e., only motions in heave and pitch direction are studied whereas, motion along the other axes is not considered here. Furthermore, few assumptions are ensured for added simplifications:

- The USFG is considered to be in hydrodynamic equilibrium. This leads to no coupling in the hydrodynamic terms due to symmetry, as all the forces act on the center of gravity (COG) of the glider.
- UiS subsea glider functions far off the region where wave effects are dominant: loading due to waves is insignificant in addition, currents are not considered.

4.1. Proportional-integral-derivative controller

Proportional-integral-derivative (PID) type control is adopted for the system under consideration, owing to its popularity amongst autonomous underwater and marine vehicles for varying the motion and obtaining desired performance of the vessel along the axis under consideration. To adduce, pitch motion for Slocum [12] is regulated by implementing a proportional controller to control internal kinetic mass.

The Control system for the glider is depicted in Figure 6 below, two PID controllers are used to control heave and pitch separately and the glider block represents the system dynamics. Desired response for operating conditions, i.e., heave and pitch, is generated from the pilot block which is then fed to the error detector. Afterward, it is then processed by the controller to produce a stimulating signal which is transformed into the desired motion.

The main task is to control the heave along with pitch motion of the USFG, which is achieved by designing a PID controller based on single input and output. For instance, if $U(s)$ in equation (3) depicts a transfer function of a particular control loop and $U_c(s)$ in equation (4) characterizes a PID based controller:

$$U(s) = K_p(1 + \frac{1}{T_i s} + T_d s) \tag{3}$$

T_d, T_i and K_p are called derivative time, integrator time, and proportional gain, respectively. These are the parameters that can be tuned for a PID controller to get the optimal performance. Whereas, in time-domain, it is expressed as:

$$u(t) = K_p\, e(t) + K_i \int_{to}^{t} e(\tau) d\tau + K_d \dot{e} \tag{4}$$

where $K_i = K_p/T_i$ is called the integral gain and $K_d = K_p T_d$ is termed as derivative gain. Error signal $e(t)$, is the difference between the desired value and the actual value of the output signal.

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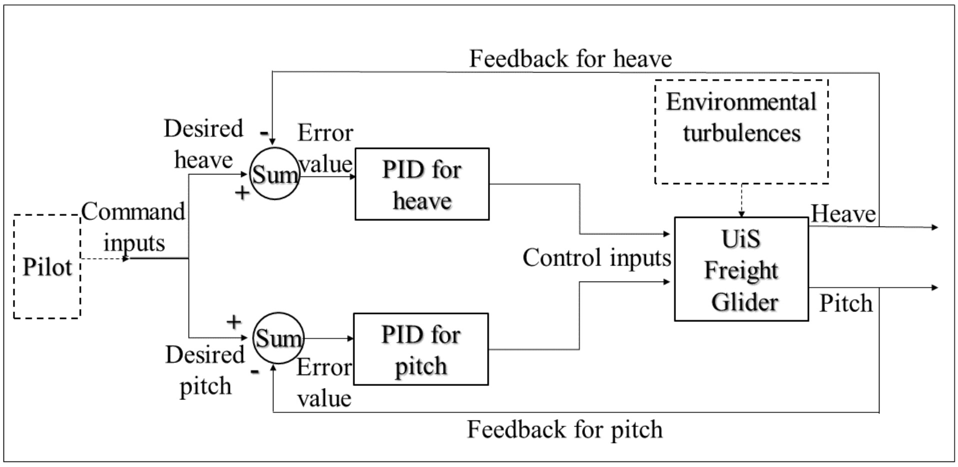

Figure 6. Control block for the glider system.

4.2. Controller Tuning

Gains for the PID controller are tuned by linearized analysis of the system along with experiments and experience of the control engineer. MATLAB transfer function-based PID Tuner App is used for this paper. The basic tuning principles for the utilized method are highlighted in Åström and Hägglund [13]. For tuning purposes, the tuner app utilizes a model which is linearized for a functional point. System step or impulse response can be obtained by altering the phase margin and bandwidth of the signal in the frequency domain, by doing this; the equivalent tuner gains can be acquired automatically. Consequences of varying the bandwidth and phase margin on different parameters like percentage overshoot (yield value which surpasses its final time-dependent value), rise time (time required by the signal to move from 10% to 90% of the yielding value), and settling time (time taken by the oscillating signal to reach 2% of the final value) are discussed in the following sections.

4.2.1. Effects of phase margin. Phase margin, which is defined as the negative phase disturbance that compels the system to be slightly stable. Figure 7 underneath displays a step plot presenting the contrast between changing the phase margin from 50° to 90° for block and tuned response respectively for heave and pitch motions.

Increasing the phase margin expands the transient behavior of the response, making the system more robust as the percentage overshoot is significantly reduced. Whereas, controller gains are reduced consequently, as seen in Table 2, leading to the increased rise time and the settling time, resulting in a less aggressive control system. Contrary behavior is observed if the phase margin is reduced which can be seen in terms of block response in Figure 7.

Table 2. PID gains for phase margin behavior.

Gains	Tuned (Heave)	Block (Heave)	Tuned (Pitch)	Block (Pitch)
K_P	164	1662	28	284
K_I	0.19	19	0.03	3.27
K_D	31229	29478	5329	5031

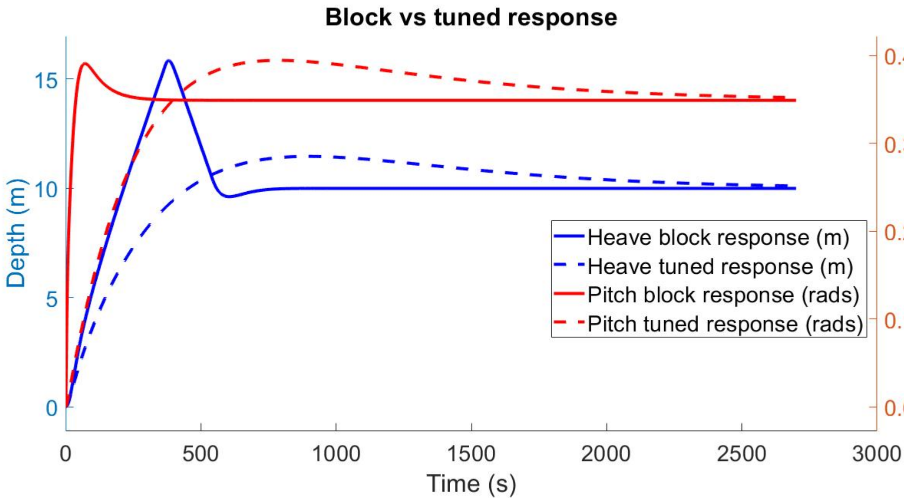

Figure 7. Response for varying phase margin.

4.2.2. Effects of bandwidth. Bandwidth sometimes referred to as response time, is defined as how fast the system retorts to changes in the input or desired conditions. Figure 8 beneath demonstrates control loops' step plot representing distinction amongst shifting response time from 0.20 for block response to 0.35 seconds for the tuned signal.

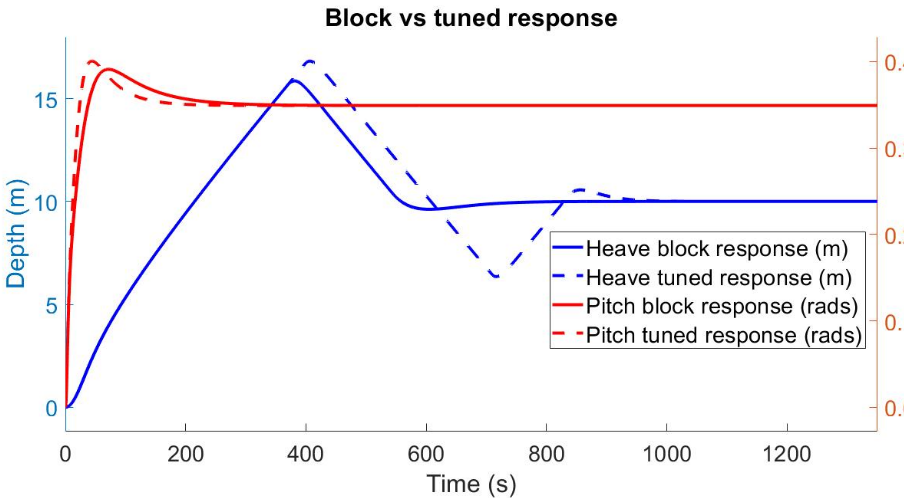

Figure 8. Varying bandwidth response.

Increasing the bandwidth of the controller for the tuned response makes the system more aggressive and agile to changes. It was observed that increasing the bandwidth to a larger value doesn't always help, instead of increasing it beyond a certain threshold induces oscillations (a reference to the tuned signal of heave in Figure 8) and makes the system unstable. Furthermore, rise time and response time are reduced as a consequence of higher controller gains (K_p, K_i, K_d) as illustrated in Table 3. On the other hand, contradicting behavior can be seen with the block response in Figure 8 in which the system is relatively lagging due to increased rise and settling time along with lower gains. As for overshoot, it can be noticed that for both cases it is quite similar, in other words, bandwidth, in this case, doesn't influence the peak of the response.

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Table 3. PID gains for response time performance.

Gains	Tuned (Heave)	Block (Heave)	Tuned (Pitch)	Block (Pitch)
K_P	4956	2333	846	284
K_I	93	34	16	3.27
K_D	51727	37367	8827	5031

Subsequent conclusions were drawn:

- Phase margin decreases overshoot, whereas bandwidth has no effect over it.
- Bandwidth, when increased minimalizes rise time, while no change is observed with varying phase margin.
- The bandwidth of 0.3 rad/s and phase margin of 90 degrees is selected from the tuning exercise.

5. Sensitivity analysis

This exercise is performed to study how the vessel response changes over time for varying ballast fraction (*BF*) and pumping capacity (*Cp*) of the pump. The focal idea behind this is to formulate few cases, as illustrated in Table 4, to study the effects of changing ballast fraction (*proportion of dead mass used for ballast*) and pumping volume (*Volumetric flow rate of ballast*) of the pump on the dynamics of the glider.

Table 4. Characteristics of sensitivity study.

Case no.	Ballast Fraction (BF) %	Pump Flowrate (Cp) m^3/h
Case 1	0.15	2000
Case 2	0.075	1000
Case 3	0.30	4000

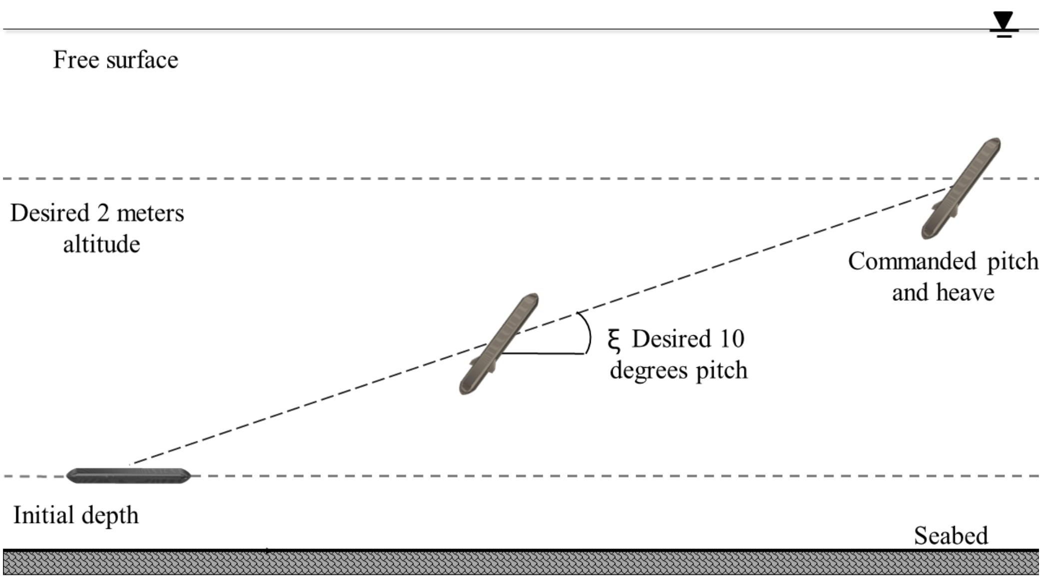

Figure 9. Test case simulation.

As a test case, the glider is instructed to attain an altitude of 2 meters long with a pitch angle of 10 degrees as depicted in Figure 9. Each case highlighted in Table 4 above was simulated to study how sensitive the USFG is to deviations in two vital parameters.

Figure 10 shows the discrepancies amongst diverse heave responses of the glider under various conditions mentioned earlier, it must be noted that the output signal is not plotted for the entire time series for better visualization and comprehension.

Output response for the 3rd case has the best performance amongst the three cases, this is because the glider generates more buoyancy force consequently due to higher ballast fraction. Moreover, as a result of increasing pump flow rate, ballast is changed efficiently and quickly, which translates to the glider attaining the desired heave and pitch quickly with no fluctuations. On the other hand, oscillations can be seen for the 2nd case in the output response making the system unstable and less robust to changes. It takes excessive time by the glider with adverse overshoot and undershoot to settle on its desired state if these conditions are used. The first case, as proposed by Xing [6] is only used as a benchmarking tool to study the effects of increasing ballast fraction and flow rate on the glider and vice versa.

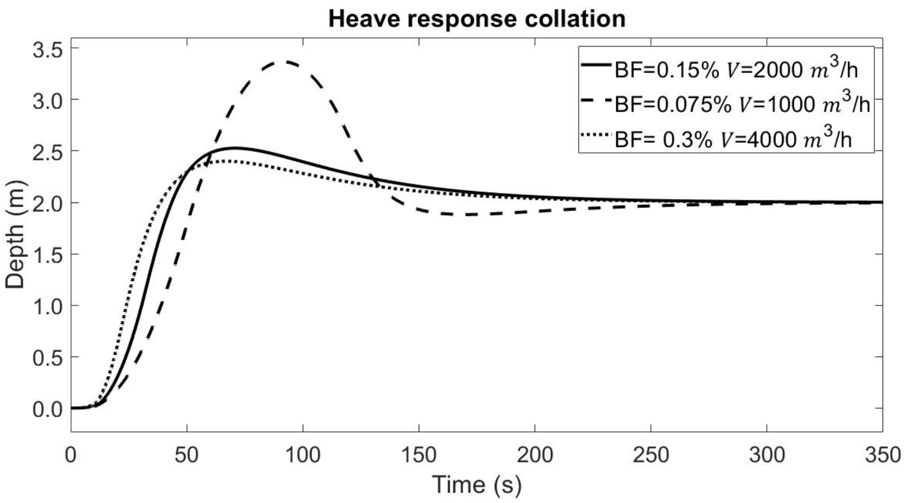

Figure 10. Heave responses for the scenarios.

The advantage of using a ballast fraction of 0.30% and a volumetric flow rate of 2000 $\frac{m^3}{h}$, i.e., Case 3, is two folds: the ability of the system to handle disturbances is significantly improved: enhanced robustness, along with faster response time. Contrarily, there are some added shortcomings, using a large pump for higher flow rates along with bigger and bulkier ballast tanks to accommodate for increased ratio. In the author's opinion, it is better to select a low power pump and small ballast tanks, i.e., 1st case, since there is not much of a variance between the results of both cases as seen in Figure 10 above.

6. Case studies

To completely define a glider, its steady glide paths must be clearly described. For this purpose, few test cases, presented in Table 5, were set up to fully understand the changing behavior of the glider concerning controller gains.

The variables studied for this analysis are the diving depth and the required pitch angles attained by USFG for the glides. The initial or base case termed as Case A signifies that the glider tries to achieve the height of 200 meters while pitching at an angle of 38°with the tuned gains chosen earlier. Moreover, it is used for benchmarking other cases operating under various conditions.

Table 5. Simulated cases.

Case name	Required depth (m)	Pitch angle (deg)	Bandwidth (rad/s)	Phase margin (deg)
Case A	200	38	0.2	90
Case B	200	19	0.3	90
Case C	200	19	0.4	90

7. Results and discussions

7.1. Effects of tuning

The results of different tuning cases for glide paths in vertical planes are presented in Figure 11 along with time series for pitch response of the USFG in Figure 12.

Reducing the bandwidth affects the system response critically as depicted in Figure 11 and Figure 12 for Case B. Lowering the bandwidth value leads to poor system response, as it becomes slower and also shows excessive overshoot and undershoot from target values. This can also be seen in the pitch response, where it takes greater time for the system to obtain the desired pitch angle.

Case C, being the ideal amongst the alternatives has the smallest response time due to aggressive tuning. It can be seen in the plots below that for this particular case the glider is quick to respond to changes in the heave and pitch motions. Moreover, for this case, deviations in the upper and lower limits are also condensed leading to reduced overrun and undershoot. Gains obtained for this case enable the system to follow the intended path closely as compared to the alternatives. Further optimizing these gains can reduce the error significantly, thus leading to enhanced performance of the USFG while gliding.

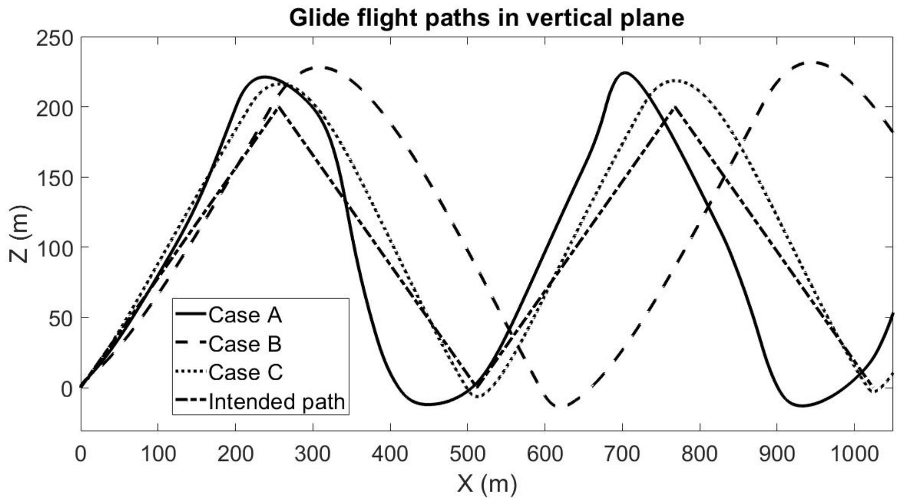

Figure 11. Glider path in a vertical plane from simulation.

Case A represents the base case gains, these controller gains were obtained in section 4.2. . It can be seen in the figure above that even the best PID gains i.e., Case C, obtained from the linear model of the system i.e., the USFG model, failed to follow the intended path. Moreover, the responses are quite slow for disturbances introduced into the system as compared to the desired case.

An error of 13 to 8 % is induced into the system for gains of Case B and Case C respectively. Also, this is likely to induce adverse effects on the glider trajectory, since at every oscillation the glider travels a significant amount of distance which was not initially intended. This is due to excessive overshoot and undershoot induced by the controller parameters and can offset the USFG from its course by a compelling margin.

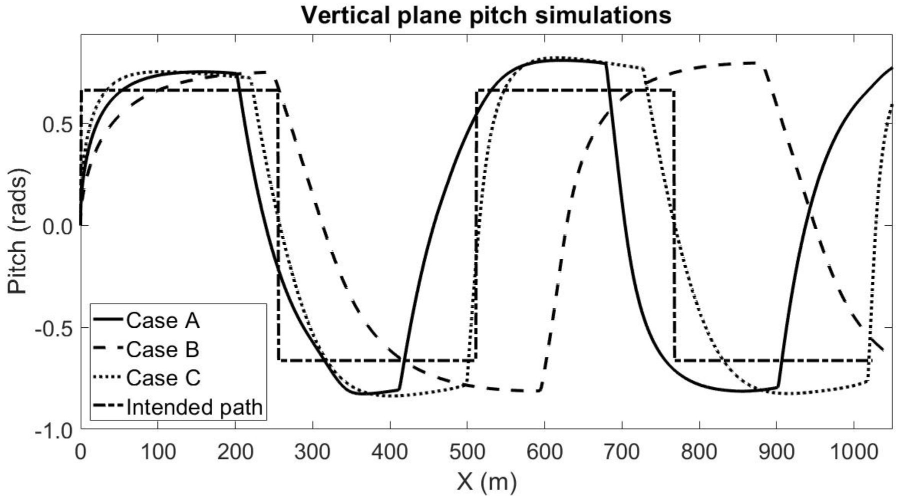

Figure 12. Vertical plane pitch state.

7.2. Best controller gains

Selecting the best parameters for (K_p,K_i, K_d) for both the controllers is a challenging and cumbersome task, but it can be done with excessive research and further developments. Following observations are made in response to selecting the best gains:

- Increasing the phase margin to the maximum value of 90° can minimize the overshoot but it does not completely diminish it as even the best gains still have an 8% overshoot.
- Improving the value of bandwidth to a certain limit i.e., 0.4, can help with the system response; making it agile, afterwards, it has no effect.

8. Conclusions

This study presents a 2D mathematical model of the UiS subsea freight-glider. Along with the model, quality assurance for the presented model has also been completed in the form of controller tuning and sensitivity analysis. The results from the case studies convey that tuning the system only by utilizing time responses obtained from a linearised model does not yield the best results. Lastly, it was observed that enhanced performance can be obtained by re-tuning the controllers for higher bandwidth, leading to better system response.

Since the equilibrium glides for the USFG should stringently follow the planned path shown in Figure 2, optimization of the PID controllers to allow for enhanced, robust, and optimal controls will lead to ideal performance. This will be the target study for future work.

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