Doctoral Thesis in Vehicle and Maritime Engineering

On the Performance of Long-Range Autonomous Underwater Vehicles

Enhancing the Endurance of AUVs

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Abstract

Autonomous underwater vehicles (AUVs) are robotic platforms that are commonly used to gather environmental data, provide bathymetric images, and perform manipulation tasks. These robots are used not only for scientific, but also for industrial and military purposes. Climate change, political instabilities, and the increasing demand for both renewable and fossil energy sources have created a need for high-performance AUVs and particularly long-range AUVs.

The performance of long-range AUVs is characterised by several parameters, such as autonomous decision making, accurate navigation, system reliability, and vehicle endurance. The vehicle's endurance is the key capability enabling long-range missions and is determined by the energy capacity and power consumption. By cruising at optimum speed, the vehicle endurance can be utilised most efficiently, resulting in the longest achievable vehicle range. The range of AUVs can be extended by maximising the available energy capacity and by minimising the overall power consumption. This thesis shows how the choices of propulsion system and power source can help improving the range of AUVs.

The power consumption comprises the hotel load and propulsive power. While the hotel load is largely depending on the payload sensors, the propulsive power can be minimised by choosing the right propulsion system. As a part of this thesis, the transit performance of underwater gliders is analysed using an analytical approach. The analysis yields a glide metric for the assessment of the energy efficiency of underwater gliding and allows for comparison to other conventional propulsion systems.

The most common energy systems for AUVs are primary and secondary electrochemical cells, in particular lithium-ion batteries. Alternative energy systems such as fuel cell (FC) systems can potentially improve the range of AUVs. Through a conceptual design study using off-the-shelf components, it is shown how FC systems can increase the energy capacity of AUVs. FC systems are typically implemented as hybrid systems paired with a small capacity battery system. Energy management strategies (EMS) are required to coordinate these two power sources. In this thesis, deterministic and optimisation-based strategies have been tested in simulations and evaluated against realistic AUV power consumption data from field trials. The results suggest that the complexity of the EMS needs to grow with mission complexity. While deterministic methods can yield the lowest energy consumption for standard missions (e.g. bathymetric imaging), optimisation-based methods provide best load-following behavior, making these methods better suited

for retaining power reliability through maintaining battery state of charge.

Keywords

Sammanfattning

Autonoma undervattensfarkoster (AUV) är robotplattformar som vanligtvis används för att samla in miljödata, tillhandahålla batymetriska bilder och/eller utföra manipulationsuppgifter. Dessa robotar används inte bara för vetenskapliga, utan också industriella och militära ändamål. Klimatförändringar och politiska instabiliteter har skapat ett ökat behov av AUV:er med lång räckvidd som till exempel kan samla in oceanografisk data från under avlägsna antarktiska istungor eller utföra undervattens- och spaningsuppdrag för att säkerställa landets säkerhet. Idag hindras AUV:er i sin operation ofta av sin begränsade räckvidd och är dessutom generellt tvingade att färdas i låg hastighet. Ökad användning av AUV:er är därför starkt beroende av val av optimalt framdrivnings- och energisystem.

Konventionella framdrivningssystem omfattar propellrar och flytkraftsmotorer. Som en del av detta doktorsarbete analyseras analytiskt transitprestanda hos undervattens- glidare. Analysen ger ett "glide-metric" som möjliggör snabb och enkel bedömning av effektiviteten av undervattensglidning med hjälp av fordonens hydrodynamiska koefficienter för lyft och motstånd – parametrar, som vanligtvis erhålls och finns tillgängliga under designprocessen. Resultaten visar vidare att för Myring-formade kroppar kan undervattensglidning vara den mest effektiva framdrivnings-metoden, givet en effektiv design av flytkraftsmotorn.

Idag drivs de flesta AUV:er av laddningsbara litiumjonbatterier. En alternativ lösning för att öka användbarheten av AUV:er är implementeringen av bränslecellssysteme (FCS). Genom konceptuell design med användning av färdiga komponenter visas i detta arbete hur FCS:er kan överträffa Li-ion-system när det gäller energitäthet på systemnivå. FC-systemet implementeras vanligtvis som hybridsystem parade med ett batterisystem med liten kapacitet. Energy Management Strategies (EMS) krävs för att samordna dessa två kraftkällor. Både deterministiska och optimeringsbaserade strategier har testats i simulering och utvärderats mot realistiska AUV-strömförbrukningsdata från fältförsök. Eftersom bränsleekonomi bara är en av flera utvärderingsparametrar, förutom t.ex. krafttillförlitlighet och systemförsämring, visar resultaten att komplexiteten hos EMS måste växa med uppdragets komplexitet.

Nyckelord

Acknowledgments

This thesis is dedicated to my mother Bettina and my grandparents Gerda & Willi, to whom I will be forever grateful for their love and support.

Stockholm, May 2022
Clemens Deutsch

Dissertation

This doctoral thesis consists of an extended summary and the following appended papers:

Paper A

C. Deutsch, L. Moratelli, S. Thuné, J. Kuttenkeuler and F. Söderling, "Design of an AUV Research Platform for Demonstration of Novel Technologies," *2018 IEEE/OES Autonomous Underwater Vehicle Workshop (AUV)*, 2018, pp. 1-8, doi: 10.1109/AUV.2018.8729729.

Paper B

Clemens Deutsch, Jakob Kuttenkeuler, Tomas Melin, *Glider performance analysis and intermediate-fidelity modelling of underwater vehicles*, Ocean Engineering, Volume 210, 2020, 107567, ISSN 0029-8018, doi: 10.1016/j.oceaneng.2020.107567.

Paper C

C. Deutsch, A. Chiche, S. Bhat, C. Lagergren, G. Lindbergh and J. Kuttenkeuler, "Energy Management Strategies for Fuel Cell-Battery Hybrid AUVs," *2020 IEEE/ OES Autonomous Underwater Vehicles Symposium (AUV)*, 2020, pp. 1-6, doi: 10.1109/ AUV50043.2020.9267932.

Paper D

Clemens Deutsch, Ariel Chiche, Sriharsha Bhat, Carina Lagergren, Göran Lindbergh, Jakob Kuttenkeuler, *Evaluation of energy management strategies for fuel cell/battery-powered underwater vehicles against field trial data*, Energy Conversion and Management: X, Volume 14, 2022, 100193, ISSN 2590-1745, doi: 10.1016/ j.ecmx.2022.100193

Paper E

C. Deutsch, S. Thuné, A. Terán Espinoza and J. Kuttenkeuler, "Fuel Cells in Practice: Challenges and Benefits for AUVs," *OCEANS 2022 - Chennai*, 2022. *Accepted in December 2021.*

Division of work between authors

Paper A

All authors have been involved in the conceptual design of the autonomous underwater vehicle (AUV) *LoLo*. Kuttenkeuler, Thuné, and Moratelli have designed and implemented the software architecture. Söderling has developed the variable buoyancy system (VBS). Deutsch carried out the hydrodynamic analysis. Deutsch has also authored the paper. The work was supervised by Kuttenkeuler.

Paper B

The project was conceptualised by Deutsch on the basis of a research idea by Kuttenkeuler and Melin. The hydrodynamics model was developed by all authors, with Deutsch taking a leading roll in model tuning and validation. Deutsch also carried out the formal analysis of the flight mechanics of underwater gliders and the assessment of their transit performance. The article was written by Deutsch with Kuttenkeuler and Melin providing feedback.

Paper C & Paper D

The project was conceptualised by Chiche, Deutsch, and Bhat. The power consumption data was collected by Deutsch and Bhat. The deterministic energy management strategies (EMSs) were developed by Chiche and Deutsch, whereas the proposed quadratic cost function for optimisation-based EMS was developed by Deutsch. Deutsch has also processed the experimental power consumption data. The simulation model for **Paper C** was developed by Chiche and Deutsch. The Simulink®-based simulation model for **Paper D** was implemented by Deutsch. The formal analysis of the results was carried out jointly by Deutsch, Chiche and Bhat. The articles were written by Deutsch as lead author, Chiche and Bhat. Lagergren, Lindbergh, and Kuttenkeuler have supervised the work and provided feedback on the articles.

Paper E

The paper was written by Deutsch. Deutsch was also responsible for data curation (gas cylinder data) and performed the comparison of energy densities for the different power system designs. The underlying design of the fuel cell/battery hybrid system is the result of a feasibility study involving Deutsch, Thuné, Terán Espinoza and external collaborators. Kuttenkeuler has supervised and reviewed the work.

x | Division of work between authors

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List of acronyms and abbreviations

AUV autonomous underwater vehicle

COT cost of transport

DR dead reckoning

DVL Doppler Velocity Log

EMS energy management strategy

ENV environmental sensing

FC fuel cell

ICE internal combustion engine

IMU inertial measurement unit

JAMSTEC Japan Marine Science and Technology Center

LBL long baseline

Li-ion lithium-ion

LiPo lithium-ion polymer

NiCd nickel-cadmium

NiMH nickel-metal hydride

OP ocean production

PEM proton-exchange membrane

PEMFC proton-exchange membrane fuel cell

SBL short baseline

SEC safeguarding society

SLAM simultaneous localisation and mapping

SMaRC Swedish Maritime Robotics Centre

SoC state of charge

SoH state of health

SSF Swedish Foundation for Strategic Research

USBL ultra-short baseline

VBS variable buoyancy system

Chapter 1

Introduction

Unlike planet Earth's name suggests, Earth is a planet of oceans. The oceans and marginal seas cover more than 70% of the planet's surface [1], most of which are only little explored by humans. Merely a fraction of the oceans are shallow coastal waters, with most parts of the oceans reaching depths of 3000 m and more [1]. The oceans are of major importance for humankind as they provide food resources, play vital roles in the planet's climate physics [2], and represent vulnerable national boundaries (a potential homeland security risk).

In the past centuries, ships and ship-borne technologies have been the main contributors to ocean observations. However, the use of ships as primary platforms for the collection of oceanographic data is costly, weather-dependent, and provides only spatially and temporally limited data in terms of resolution. In order to fully and efficiently study, utilise, and monitor the oceans, there is a need for robotic platforms that can access even the deepest and remotest regions [3].

Autonomous underwater vehicles (AUVs) are robotic platforms that are designed to carry payloads in accordance with the operator's needs. The payloads typically comprise environmental sensors, acoustic imaging sonars, cameras [4], and manipulators [5]. As such, AUVs can be considered to be an extension of the human reach, extending our grasp and senses into the depth of the oceans.

The main applications of AUVs include science, environmental monitoring, offshore industries, military/security and others, such as underwater inspection [6, 7]. It is inevitable, that unlocking longer mission range and endurance will benefit all operators of AUVs: Increasing the maximum mission length of AUVs will help

not only scientists to sample environmental data from yet inaccessible regions, but also governmental bodies to perform long-term ocean observation. Long-term ocean observations will help governments to better align policies with climate goals and aid the military in executing long-range underwater reconnaissance.

1.1   Swedish Maritime Robotics Centre

The research in this thesis is funded by the Swedish Maritime Robotics Centre (SMaRC). SMaRC is an industrial research centre funded by the Swedish Foundation for Strategic Research (SSF) under grant number IRC15-0046. Founded in 2017, SMaRC has created a collaborative research environment that brings together academia, key industries, and governmental partners in Sweden. The centre's research focus lies in the development towards next-generation maritime robots. SMaRC has identified three societal benefits as its main drivers:

- **Ocean production (OP)**: Utilisation of the oceans as sustainable sources of food, energy, and raw materials.

- **Safeguarding society (SEC)**: Surveillance and reconnaissance of national territories, particularly coastal and offshore waters.

- **Environmental sensing (ENV)**: Oceanographic surveying, including measuring of physical, biological, and chemical ocean data.

The research centre's primary objective is to serve the societal benefit areas through a holistic approach to improving AUV system performance. Following this holistic approach, SMaRC is focusing on the following research areas: Autonomy, endurance, perception, and communication (Fig. 1.1).

The work carried out in these research areas mainly targets the application of two types of AUVs: Long-range AUVs and man-portable, affordable AUVs. As part of a demonstrator program, SMaRC is designing, developing and testing both hardware and software for the two demonstrator platforms AUV *LoLo* [8] and AUV *SAM* [9, 10]. The technologies and capabilities developed by researchers in SMaRC are continuously tested and demonstrated through the demonstrator program [11].

Within the scope of SMaRC, this thesis is addressing the endurance of AUVs, with a particular focus on the performance of long-range AUVs.
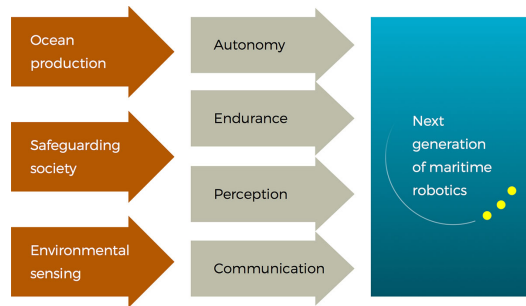
Figure 1.1: Research focus of the Swedish Maritime Robotics Centre (SMaRC).
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1.2 Performance of Long-Range AUVs

Performance is an artificial concept and as such its definition is rather vague and its perception largely depends on the audience and the context. The term *performance* can include aspects of reliability, payload capacity, maneuverability, speed, autonomy, navigation, endurance, and range (Fig. 1.2).

Arguably, all of these aspects contribute towards the vehicle's performance. But not only so, there are also interdependencies between each of these aspects of performance: E.g., the endurance and range of AUVs is strictly dependent on vehicle speed. Therefore, essentially all of these aspects have become research topics of their own within the field of underwater robotics. In order to provide a general overview, the main research fields are briefly summarised in this section.
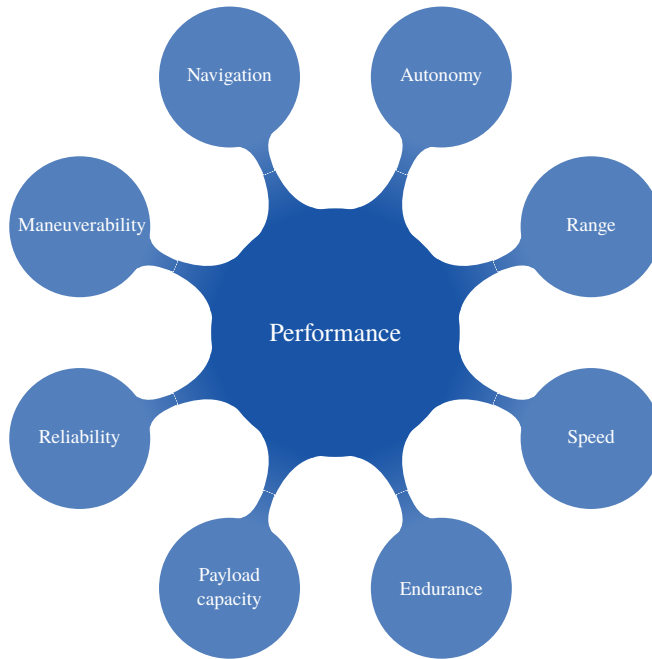
Figure 1.2: Main parameters influencing the performance of AUVs

Localisation and Navigation

Localisation deals with the identification of position and orientation (*pose*) of the vehicle. Sufficiently accurate localisation is a fundamental prerequisite for AUV navigation, in particular for missions where the sampled data is georeferenced. Since the navigational error grows with time, navigation accuracy can be a bottleneck for the performance of long-range AUVs.

Dead reckoning (DR) is the primary navigation method for AUVs. DR uses data from inertial measurement units (IMUs) for the estimation of vehicle pose and velocity. IMUs consist of accelerometers, gyroscopes, and compasses or magnetometers. These sensors, however, are prone to sensor drift that causes DR to have unbound error growth. Typically, Doppler Velocity Logs (DVLs) complement the IMU to improve navigation accuracy [12]. In certain cases, triangulation using ultra-short baseline (USBL), short baseline (SBL) or long baseline (LBL) acoustic positioning systems can be used to improve navigation [13]. These positioning systems, however, require additional reference points with known locations (typically surface

buoys or ships).

Latest research on AUV navigation is focusing on advanced simultaneous localisation and mapping (SLAM) techniques, in which localisation is performed while creating a map of the environment [13]. In most cases, these maps are created using acoustic imaging and visual sensors (cameras). Loop closures, i.e. the repeated observation of a previously mapped feature, are used to correct the accumulated error and thus improve the map quality and localisation accuracy [14, 15].

Autonomy

Autonomy, or more precisely *decision autonomy*, is the vehicle's ability to recognise, process and adapt to unexpected situations and deviations from a previously defined mission plan [4, 16]. Particularly on long-range missions, unexpected events that can compromise the mission plan become more likely to occur. Therefore, it is important that the vehicle has high levels of decision autonomy.

Autonomy plays particularly critical roles in the following scenarios: Collision avoidance, fault-tolerance, mission replanning, and multi-agent coordination. Ongoing research on improving the autonomy of AUVs includes, for example, the integration of behavior trees into path planning [17] and multi-agent control, as well as dynamic Bayesian networks for fault detection, isolation and recovery (FDIR) systems [18].

Maneuvering

Most AUVs are underactuated robots, i.e. these vehicles have actuation in fewer than 6 degrees of freedom [19]. The better the maneuvering capabilities of an AUV, the more degrees of freedom can be controlled. Control of additional degrees of freedom increase the performance of AUVs by enabling more agile maneuvers. Agile maneuvers can facilitate the use of imaging sonars in multiple directions by changing the orientation of the vehicle. Ongoing research is focusing on clever control algorithms to perform advanced hydrobatic maneuvers with underactuated AUVs [9].

Endurance and Range

Endurance and range are key capabilities of AUVs. The two terms, endurance and range, are closely related and coupled through the vehicle's speed; at optimal speed, the AUV will travel the farthest, while at lower speed the AUV will operate for the longer period of time. The benefits of enhancing endurance and range are two-fold:

1. Temporal aspect: Performing longer missions decreases the need for ship time and human intervention. Both of these factors are cost-critical. Furthermore, increased endurance enables long-term ocean observation.

2. Spatial aspect (range): Performing longer missions grants access to yet inaccessible regions.

The endurance of long-range AUVs can be improved in several ways. Maximising vehicle endurance is a matter of maximising the power system's energy budget and minimising the system's energy consumption.

1.2.1 Range and Endurance of AUVs

The terms *range* and *endurance* are often used in the same context and, in fact, both concepts are closely related. Endurance describes the maximum achievable mission duration, whereas range describes the maximum achievable travel distance. Both, the vehicle's range and endurance depend on the available energy capacity and the overall power consumption. Mathematically, the achievable endurance $\mathcal{E}$ and range $\mathcal{R}$ can be expressed as

$$\mathcal{E} = \frac{E}{P}, \tag{1.1}$$

$$\mathcal{R} = \frac{E}{P}U, \tag{1.2}$$

where E is the energy capacity of the vehicle, P is the overall power consumption, and U is the vehicle speed. The power consumption of AUVs is often expressed as the sum of propulsive power P_p (see Ch. 2) and hotel load P_h:

$$P = P_p(U) + P_h \tag{1.3}$$

The propulsive power is mainly determined by the AUV's hydrodynamic and maneuvering characteristics, i.e. the vehicle's hydrodynamic drag is strictly dependent on the vehicle speed and control actuation for depth or course changes (turning). Beyond hydrodynamic drag, the propulsion system's mechanical efficiency is affecting the propulsive power.

The hotel load is defined as the power consumption which is not directly related to propulsion. As such, the hotel load includes power consumption from e.g. board computers, communication systems, navigation systems, and payload sensors (such as acoustic imaging sonars and CTDs). The hotel load is characterised by a constant

power level with intermittent changes (depending on active and inactive sensors).

As can be seen from Eq. (1.1) and Eq. (1.2), both endurance and range are speed-dependent (the propulsive power is a function of speed): The endurance strictly decreases with increasing vehicle speed (due to increasing power consumption), whereas the maximum range is achieved at an optimal speed [20] (Fig. 1.3).
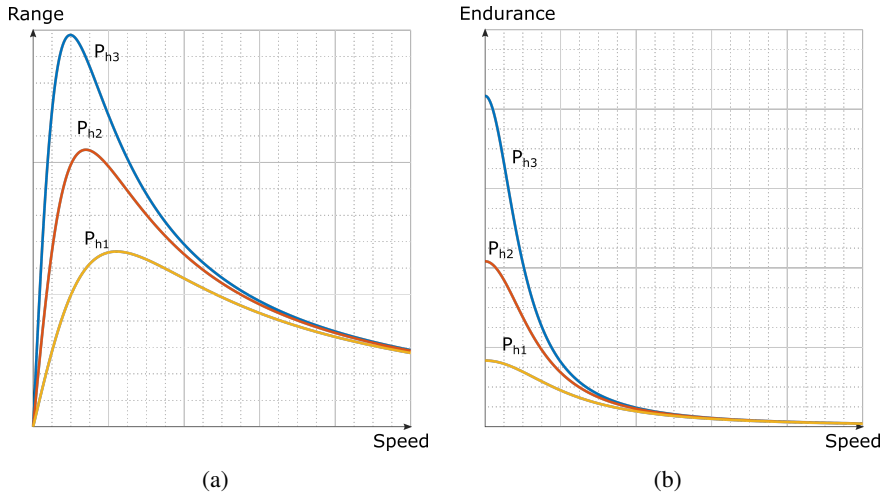
Figure 1.3: Examples of vehicle range and endurance plots. Each curve corresponds to a certain hotel load P_h. **(a)** Range plot **(b)** Endurance plot

1.3 Applications of Long-Range AUVs

Extended range and endurance are key requirements for the successful operation of AUVs on certain missions. Within SMaRC, especially the two benefit areas ENV and SEC lead to the need for long-range operation of AUVs. Two examples of possible applications that require long-range AUVs are highlighted in this section.

1.3.1 Below-Glacier Monitoring

Monitoring of marine subglacial environments (Fig. 1.4) has become one of the most difficult and at the same time most important fields of ocean research. Fast and irreversible melting of glaciers and ice shelves can destabilise the polar ice caps, with potentially disastrous consequences for the planet. However, scientists

are lacking data for understanding of underlying geophysical processes and for the quantitative assessment and prediction of the stability of the polar ice caps [21].

In order to acquire more data that can facilitate further knowledge of the involved geophysical processes, it is necessary to travel up to $500\,$km and more under the ice shelves. [22, 23, 24, 25].

Figure 1.4: Scenario: Below Glacier Monitoring. ©SMaRC

1.3.2 Long-Range Reconnaissance

With recent advances in smart technology and a shift from conventional warfare to the deployment of both stealth and autonomous weapon & intelligence systems, there is a growing demand among military and defence agencies to provide long-range underwater reconnaissance (Fig. 1.5). In SMaRC, these missions have been estimated to require at least $400\,$km in range.

Figure 1.5: Scenario: Long-Range Reconnaissance. ©SMaRC

1.4   Research Scope and Structure

This thesis addresses the endurance of long-range AUVs. The endurance of long-range AUVs is constrained by several parameters (also see Fig. 1.6):

Energy Systems: The size and type of energy system affects the amount of usable energy (energy capacity).

Propulsion Systems: The means of locomotion and the drive train of the propulsion system affect the power consumption for propulsion.

Hydromechanics & Flight Mechanics: Hydrodynamic drag increases the required propulsive power and therefore the power consumption.

Autonomy: Accurate navigation, adaptive mission and path replanning, and effective collision avoidance enable sustained long-range missions.

Control Strategies: The use of energy-efficient controllers minimises the energy consumption for actuation of the vehicle.

The focus of this thesis lies on both propulsion systems and energy systems. By identifying best-choice solutions for propulsion and energy systems, the foundation for well-performing long-range AUVs is laid.
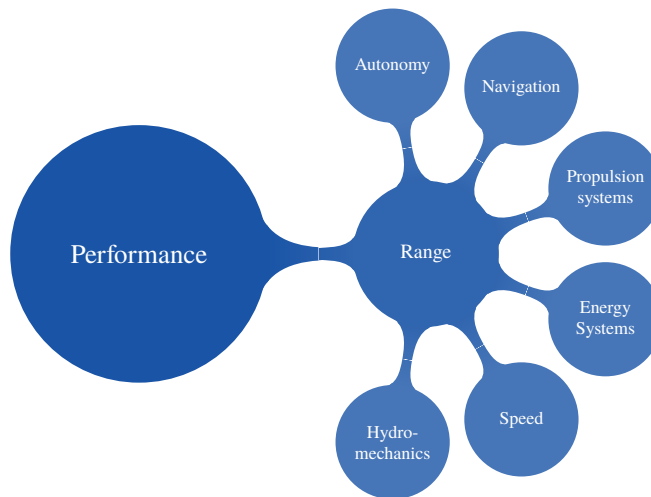
Figure 1.6: Main parameters influencing the range of AUVs. Some of these parameters contribute not only to the vehicle range, but also to overall AUV performance.

Chapter 2 provides the reader with background knowledge on locomotion of underwater vehicles. The concepts of screw propellers and underwater gliding are presented, since these mechanisms represent the state-of-the-art for underwater propulsion. The cost of transport for propeller- and buoyancy-driven propulsion is assessed. A glide metric is presented, which allows for performance comparison of propeller-based propulsion and underwater gliding on the basis of the non-dimensional hydrodynamic coefficients for drag and lift (Paper B).

Chapter 3 provides an overview of power sources for AUVs. Electrochemical cells are highlighted as the state-of-the-art for AUV power systems. The chemistry and characteristics of electrochemical batteries, particularly lithium-ion (Li-ion) secondary cells, is briefly reviewed, since their application on AUVs is constrained by the ocean environment. Alternative power sources include another type of electrochemical cell: hydrogen fuel cells. Section 3.2 provides information about fuel cell technology and their application on AUVs. Two research topics related to fuel cell technology are at the center of this work: The implementation of fuel cell systems on AUVs as well as their benefits (Paper E), and the deployment of efficient energy management strategies (EMSs) for the operation of hybrid fuel cell/battery power systems on AUVs (Paper C, Paper D).

Chapter 2

Efficient Underwater Propulsion

Underwater propulsion systems can be divided into conventional and unconventional systems. Conventional propulsion systems are generally propeller-based, whereas unconventional propulsion includes, for example, buoyancy-driven underwater gliding and bio-inspired or bio-mimetic propulsion systems. Propulsion systems are the main contributors to the overall power consumption of AUVs. Depending on the size of the AUV, the propulsive power can be in the order of several kilowatts. Efficient underwater propulsion enables AUVs to travel long distances between one or more spatial points by maximising the propulsive efficiency and minimising the associated cost of transport (COT).

The COT quantifies the energy expenditure associated with the locomotion of the vehicle from one place to another on a direct route. The COT strictly depends on the propulsive power, which is the power required to propel the fully submerged vehicle, and is determined by the resistance induced by hydrodynamic drag and the efficiency of the propulsion system. In this chapter, the COT for propeller-driven AUVs and underwater gliders is elaborated on.

2.1   Hydrodynamic Forces

In order to facilitate better understanding of the COT for different propulsion mechanisms, it can be helpful to investigate the hydrodynamic forces first. When the vehicle is moving at speed U due to some thrust T, it is subject to the hydrodynamic forces drag D and, if at a non-zero angle of attack, lift L. The drag

is acting in the opposite direction of U and the lift is acting perpendicular to the drag. In steady flight, the thrust force is equal to the drag force in magnitude but acts in the opposite direction, i.e. in the direction of travel. For further analysis, it is helpful to express D, L as a function of the non-dimensional hydrodynamic coefficients C_D, C_L:

$$D = \frac{1}{2}\rho U^2 C_D A, \tag{2.1}$$

$$L = \frac{1}{2}\rho U^2 C_L A, \tag{2.2}$$

where ρ is the density of the surrounding fluid and A is the reference area that C_D, C_L refer to (typically the cross-section area or wetted surface area).

2.2 Propeller-Driven Level Flight

Like most marine surface vessels, many autonomous underwater vehicles are propelled by screw propellers. Screw propellers consist of propeller blades that are radially mounted onto a rotating propeller hub. The propeller blades are extruded airfoil (or hydrofoil) sections, which can vary in width, chamber, pitch, and twist along their length. When rotating through a fluid body, the propeller blades are subject to the fluid dynamic forces lift and drag. The net force perpendicular to the propeller plane is called propeller thrust; for propeller-driven AUVs it is the force that accelerates the vehicle [26].

2.2.1 Cost of Transport

The propulsive power required for a propeller to move the vehicle at a constant speed is the product of thrust and vehicle speed. In steady flight, the thrust equals the total drag force, which is why the propulsive power can be written as

$$P^{\mathrm{p}} = DU. \tag{2.3}$$

Integrating Eq. (2.3) with respect to time, yields an expression for the COT in terms of energy consumed over the distance travelled (energy per unit distance):

$$\mathrm{COT^p} = D = \frac{1}{2}\rho U^2 C_D A \tag{2.4}$$

Since propellers represent the most conventional propulsion system, Eq. (2.4) can serve as a benchmark for the evaluation of other propulsion systems and vehicle

designs (through the non-dimensional coefficient for drag).

2.3   Underwater Gliding

Underwater gliding is a type of locomotion that is inherently different from propeller-driven locomotion. Underwater gliders use so-called buoyancy engines, which are hydraulic devices that provide a change in system volume or system weight. As such, buoyancy engines change the net buoyancy of the vehicle, which is the difference between buoyancy and gravity force vectors. Switching between positive and negative net buoyancy makes the vehicle alternate between rising towards the surface and sinking towards the sea floor. In combination with hydrodynamic lift, the vehicle does not only move vertically, but also horizontally, resulting in a sawtooth-like glide pattern (Fig. 2.1). The name *buoyancy engine* stems from the fact that, in body-fixed coordinates, the along-track component of the net buoyancy force is the thrust.

These considerations are important when assessing the COT of underwater gliders. The assessment of the COT is facilitated through a study of the glide mechanics (Sec. 2.3.1).
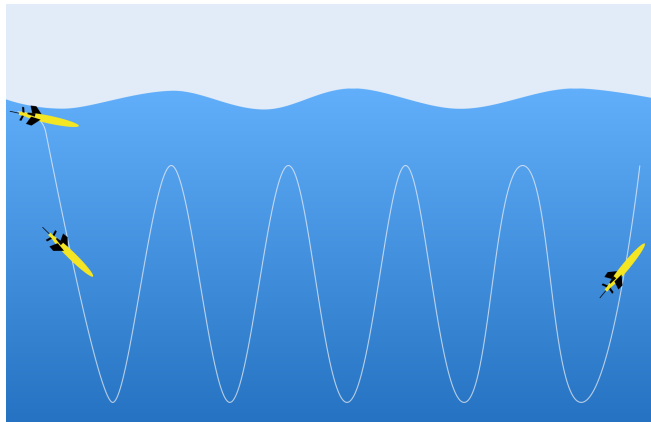

Figure 2.1: Illustration of underwater gliding.

2.3.1 Flight Mechanics of Underwater Gliding

In order to evaluate the COT of underwater gliders, it is necessary to understand the relationships between the acting forces and the state of flight. Fig. 2.2 shows the free-body diagram for the lateral projection of an underwater glider (body-fixed coordinates x, z) in a global reference frame (global coordinates X, Z). When the glider is travelling at an absolute velocity U due to a non-zero net buoyancy force B_{net}, the vehicle body is subject to hydrodynamic forces drag D and lift L.
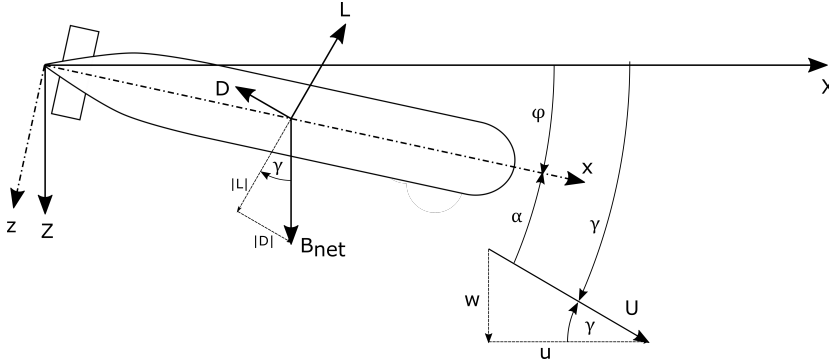
Figure 2.2: Free-body diagram showing the forces acting on an underwater glider in steady flight

The glider's flight state is characterised by the glide path angle γ, which is the difference between the glider's pitch angle ϕ and the hydrodynamic angle of attack α:

$$\gamma = \phi - \alpha \tag{2.5}$$

The flight characteristics of underwater gliders can be analysed by considering steady or unaccelerated flight (steady state), during which the sum of all acting forces F is equal to zero. For the representation in global (X, Z) and velocity-based $(U_{\parallel}, U_{\perp})$ reference frames this approach yields the following equations:

$$
\begin{aligned}
\Sigma F_X &= -D\cos\gamma + L\sin\gamma & &= 0, & &(2.6)\\
\Sigma F_Z &= -D\sin\gamma - L\cos\gamma + (B - mg) &&= 0, & &(2.7)\\
\Sigma F_{U\parallel} &= -D + (B - mg)\sin\gamma & &= 0, & &(2.8)\\
\Sigma F_{U\perp} &= -L + (B - mg)\cos\gamma & &= 0. & &(2.9)
\end{aligned}
$$

In Eq. (2.8)-(2.9), B denotes the buoyancy, m denotes the vehicle mass, and g is the gravitational acceleration. The difference $(B - mg)$ is the net buoyancy B_{net}. Closer inspection of Fig. 2.2 confirms, that the resulting glide path angle is determined by the forces acting on the glider (force triangle). The forces, in turn, determine the resulting velocities (velocity triangle). These geometric relationships can expressed using Pythagoras' theorem

$$B_{\text{net}} = \sqrt{D^2 + L^2} \qquad \text{Force triangle,}$$

$$U = \sqrt{u^2 + w^2} \qquad \text{Velocity triangle,}$$

where u (transit speed in X) and w (sink rate in Z) are the global velocity components, or using trigonometric functions

$$\tan \gamma = \frac{w}{u} = \frac{D}{L}. \tag{2.10}$$

Analogously, the relations shown in the force triangle can be derived by solving either Eq. (2.6) or alternatively Eq. (2.8) and Eq. (2.9) for the glide path angle γ.

Basic understanding of the flight mechanics of underwater gliders can also be facilitated through the analysis of energetics of underwater gliding. Following the law of conservation of energy, the change in mechanical energy (gravitational potential energy and kinetic energy) needs to be equal to the work done.

$$\text{KE} = \frac{1}{2}mU^2 \qquad \text{Kinetic energy}$$

$$\text{GPE} = B_{\text{net}}d \qquad \text{Potential energy}$$

In these equations, d is the depth of submergence. When the glider is travelling along a trajectory s, work is done on the vehicle by the hydrodynamic drag:

$$\text{W} = Ds \tag{2.11}$$

Considering the steady flight of an underwater glider travelling a vertical distance d, the conservation of energy can be written as follows:

$$B_{\text{net}}d = Ds \tag{2.12}$$

In this steady state case, kinetic energy is constant and therefore does not contribute to Eq. (2.12). From the trigonometric relations of a dive cycle (Fig. 2.3), the following relationship between the depth d and along-track distance s can be established:

$$\sin \gamma = \frac{d}{s}. \tag{2.13}$$

Solving Eq. (2.13) for s and substituting into Eq. (2.12), yields the important relationship between D and B_{net}

$$\sin \gamma = \frac{D}{B_{\text{net}}}, \tag{2.14}$$

which indeed is in agreement with Eq. (2.8).

2.3.2 Cost of Transport for Transit Flight

In order to assess the COT for transit flight of underwater gliders, the energy expenditure w.r.t. to the horizontal distance covered needs to be determined. Reverting back to Fig. 2.3, the horizontal distance covered can be expressed

$$s_h = \frac{2d}{\tan \gamma}. \tag{2.15}$$

The energy expenditure associated with propulsion is the energy consumption of the buoyancy engine. In an ideal case, actuation of the buoyancy engine is only required at the maximum depth of the dive cycle (*apogee depth*, d) since the buoyancy pump is working with the hydrostatic pressure gradient at the surface. The effective pump energy then is

$$E_{\text{BE}} = \Delta B_{\text{net}} d, \tag{2.16}$$

where ΔB_{net} is the change in net buoyancy (pump volume). Dividing Eq. (2.16) by Eq. (2.15) yields the energy consumption per distance travelled horizontally:

$$E^g = \frac{E_{\text{BE}}}{s_h} = \frac{1}{2} \Delta B_{\text{net}} \tan \gamma. \tag{2.17}$$

Unfortunately, in the present form, Eq. (2.17) is not analogous to Eq. (2.4) as it does not contain any information about the vehicle's speed. Deriving the relationship between net buoyancy and vehicle velocity is equivalent to establishing
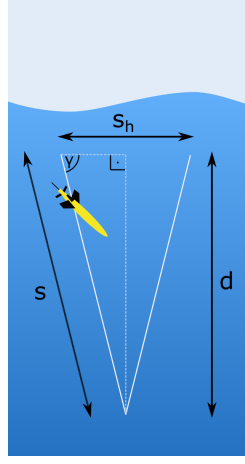
Figure 2.3: Dive cycle of an underwater glider with glide depth (apogee depth) d and travelled distance s.

a so-called glide polar [27, 28]. Here, the horizontal velocity component u is of particular importance. From the velocity triangle, it can be seen that

$$\cos \gamma = \frac{u}{U}, \tag{2.18}$$

whereas Eq. (2.8) shows that

$$B_{\text{net}} \cos \gamma = L. \tag{2.19}$$

Substituting Eq. (2.18) into Eq. (2.19) and expressing lift with Eq. (2.2), yields the following equation:

$$B_{\text{net}} u = \frac{1}{2} \rho U^3 C_L A \tag{2.20}$$

Using Pythagoras' theorem, the absolute velocity U can be substituted by the Euclidean sum of its vectorial components:

$$B_{\text{net}} u = \frac{1}{2} (u^2 + w^2)^{3/2} C_L A \tag{2.21}$$

At this point, Eq. (2.10) can be used to eliminate the sink rate w from the equation:

$$B_{\text{net}}u = \frac{1}{2}\rho(u^2 + u^2\frac{C_D^2}{C_L^2})^{3/2}C_L A \tag{2.22}$$

The horizontal velocity u on the right-hand side (RHS) of Eq. (2.22) can now be factorised and simplified to

$$B_{\text{net}}u = \frac{1}{2}\rho u^2(1 + \frac{C_D^2}{C_L^2})^{3/2}C_L A \tag{2.23}$$

Solving Eq. (2.23) for u^2 yields the following expressions:

$$u^2 = \frac{2B_{\text{net}}}{\rho A}(1 + \frac{C_D^2}{C_L^2})^{-3/2}C_L^{-1} \tag{2.24}$$

Multiplying the RHS of Eq. (2.24) by $\frac{C_L^2}{C_L^2}$ yields

$$u^2 = \frac{2B_{\text{net}}}{\rho A}(1 + \frac{C_D^2}{C_L^2})^{-3/2}C_L^{-3}C_L^2. \tag{2.25}$$

After utilising the property $C_L^{-3} = (C_L^2)^{-3/2}$ and expanding terms, the square root can be taken to derive the final expression of u as a function of B_{net} and the non-dimensional hydrodynamic coefficients C_D, C_L:

$$u = \sqrt{\frac{2B_{\text{net}}}{\rho A}}\frac{C_L}{(C_L^2 + C_D^2)^{3/4}} \tag{2.26}$$

Solving Eq. (2.26) for B_{net} and substituting into Eq. (2.17) yields the following equation for energy expenditure per distance travelled in transit:

$$\text{COT}^g = \frac{1}{2}\rho u^2 \frac{C_D\left(C_D^2(\alpha) + C_L^2(\alpha)\right)^{3/2}}{C_L^3(\alpha)}A, \tag{2.27}$$

where we denote the glide coefficient C_{GL}

$$C_{GL} = \frac{C_D\left(C_D^2(\alpha) + C_L^2(\alpha)\right)^{3/2}}{C_L^3(\alpha)}. \tag{2.28}$$

It shall be noted that Eq. (2.27) yields a good approximation of the COT given the following assumptions:

- The dive cycles are sufficiently deep, s.t. the initiation phase does not compromise the average vehicle speed (since u in Eq. (2.27) is during steady flight).

- The number of dive cycles is sufficiently large, s.t. the COT is still accurate even if the last dive cycle finishes prematurely.

- The buoyancy engine only needs to be actuated at apogee depth. The resulting change in net buoyancy is $\Delta B_{\text{net}} = 2B_{\text{net}}$.

Closer inspection of the transit COT of underwater gliders reveals an interesting analogy to the COT of propeller-driven level flight. Similarly to the dimensionless drag coefficient in Eq. (2.4), the glide coefficient (Eq. (2.28)) is a direct expression of the transit efficiency of underwater gliders. Comparing this glide coefficient for a particular glider design to the bare-hull drag coefficient yields a glide metric, which allows for quick assessment of the efficiency of the glider design. This glide metric is given by

$$\frac{C_D(C_D^2 + C_L^2)^{3/2}}{C_{D0}C_L^3} < \frac{\eta_p^G}{\eta_p^P}, \qquad (2.29)$$

where C_{D0} denotes the bare-hull drag coefficient (wingless) and $\eta_p^{G,P}$ denote the mechanical efficiency of the buoyancy engine and the propeller drivetrain, respectively. If the inequality in Eq. (2.29) is fulfilled, gliding locomotion is more efficient in transit than propeller-driven level flight (Paper B).

Chapter 3

Energy Systems for Long-Range AUVs

In general, AUVs require power sources with high energy density and relatively low power density (due to typically low current draw) [29]. Energy and power systems for AUVs have been continuously developed and improved throughout the past decades. Unlike airborne or terrestrial vehicles, the development of underwater vehicles is accompanied by several challenges: Firstly, both energy and power sources have to operate in submerged conditions, i.e. the systems have to be able to cope with the hydrostatic pressure, which leads to the need for either pressure housing or pressure-tolerant systems. Secondly, the power source needs to operate air-independently. While air-independence does not pose a problem for electrochemical batteries, power sources that rely on oxidising processes, such as fuel cells and internal combustion engines (ICEs), require on-board storage of air or oxygen.

The most common power sources for AUVs are electrochemical cells [29, 30, 31, 32]. Electrochemical cells can either be galvanic, electrolytic or both, i.e. they can produce a chemical reaction through the application of an electric current, generate an electric current through a chemical reaction, or do both. The respective electrochemical reactions depend on the choice of materials for the electrodes and electrolyte. Assemblies of multiple cells that are both galvanic and electrolytic are known as rechargeable batteries. Electrochemical cells suitable for application on AUVs include the following types:

- **Primary cells (non-rechargeable)**: Primary cells, such as alkaline and Li-ion (primary) batteries, impress with high energy density and specific energy.

Even though one-time costs are relatively low, there are significant recurring costs associated with primary cells due to the cells not being rechargeable. Therefore, primary cells are not often deployed on commercial AUVs.

- **Secondary cells (rechargeable)**: Rechargeable batteries are the most common power source for AUVs. Despite higher procurement costs, rechargeable batteries are associated with lower operative costs due to their relatively long lifetime. In the past both nickel-cadmium (NiCd) and nickel-metal hydride (NiMH) batteries have been used. However, with recent development especially in the automotive industry, lithium-ion (Li-ion) batteries have become industry standard due to their significantly better energy density.

- **Fuel cell (FC) systems**: Fuel cells are different from primary and secondary cells, since they rely on a continuous external supply of a fuel and an oxidising agent. As of today, FC systems have only been deployed on few scientific AUVs and prototypes.

Several other alternative power sources for AUVs and manned submarines have been developed. However, none of these alternative systems are considered suitable for widespread application on AUVs due to safety concerns, system complexity, and technological inferiority. Alternative power sources include the following systems:

- Thermal engines [33, 34]

- Sterling engines [35]

- Saltwater batteries [36]

- Semi-fuel cells [32, 37, 38]

- Combustion engines [39]

- Nuclear reactors [40]

- Environmental energy harvesting devices

    – Wave energy [41]
    – Gyroscopic power sources [42]

While Li-ion rechargeable batteries are the most common power source for both commercial and scientific applications, fuel cell systems hold great potential for widespread use on underwater vehicles and other submerged systems.

3.1 Lithium-ion Rechargeable Batteries

Despite having lower energy density than primary cells, secondary cells are widely used on robotic systems due to their relatively low life cycle costs. The most common secondary cell technologies for mobile applications are lithium-ion (Li-ion) and lithium-ion polymer (LiPo) cells. Depending on charge and discharge characteristics, lithium-ion rechargeable batteries have a cycle life of up to several hundreds or even thousands of charge cycles [43].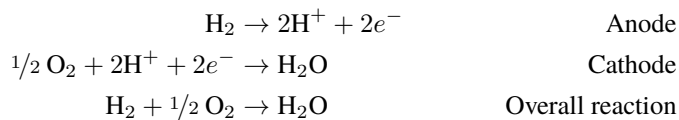 Being electrochemical cells, Li-ion batteries consist of two electrodes (anode and cathode) that are separated by an electrolyte.

An electric potential causes the lithium ions to move from the negative to the positive electrode, when the circuit is closed. When a load is attached to the circuit, the battery is discharged. If a voltage source with a potential higher than that of the battery is connected, the flow of ions is reversed and the battery is recharged (Fig 3.1a). Both electrodes can consist of different materials. The most common materials are cobalt oxide (cathode) and graphite (anode). The electrochemical reactions for this type of electrochemical cell are:

$$LiC_6 \rightleftharpoons C_6 + Li^+ + e^- \qquad \text{Anode}$$
$$CoO_2 + Li^+ e_- \rightleftharpoons LiCoO_2 \qquad \text{Cathode}$$
$$LiC_6 + CoO_2 \rightleftharpoons LiCoO_2 \qquad \text{Overall reaction}$$
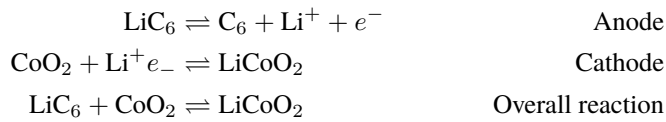
3.2 Hydrogen Fuel Cell Systems

Like Li-ion batteries, proton-exchange membrane fuel cells (PEMFCs) are electrochemical cells. From a cell architecture perspective (Fig. 3.1b), a major difference concerns the ion carrier. In hydrogen FCs, hydrogen is the ion carrier. Being the fuel, hydrogen is consumed during operation and must be externally supplied for continuous operation of the FC, which leads to challenges related to storage of hydrogen and oxygen. The electrochemical reactions for PEMFCs are:
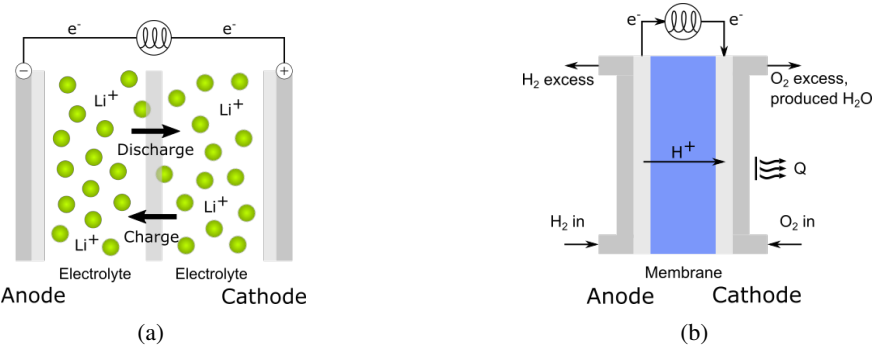
$$H_2 \rightarrow 2H^+ + 2e^- \qquad \text{Anode}$$
$$\tfrac{1}{2}\,O_2 + 2H^+ + 2e^- \rightarrow H_2O \qquad \text{Cathode}$$
$$H_2 + \tfrac{1}{2}\,O_2 \rightarrow H_2O \qquad \text{Overall reaction}$$

Figure 3.1: Electrochemical cells as power sources. **(a)** Li-ion cell **(b)** Hydrogen fuel cell

3.2.1 Fuel Cell Systems for AUVs

Fuel cell systems for AUVs have been researched and developed since the late 1990s (Fig. 3.2). The first fully operational FC-AUV was the Japanese AUV *Urashima*, which was developed by the Japan Marine Science and Technology Center (JAMSTEC) since 1998 and passed its first sea trials in 2000 [44]. *Urashima* is a large-size AUV with a length of nearly 10 m and a displacement of 7500 kg in the original configuration [44]. The fuel cell system was built around a PEMFC with gaseous supply of oxygen (from an internal gas tank) and hydrogen supply from metal hydride storage.
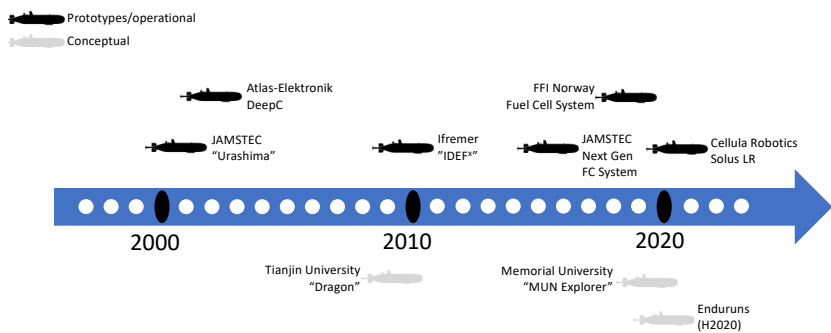

Figure 3.2: Past and ongoing FC-projects for AUVs

In 2004, a German consortium of industrial and academic institutions com-

pleted the development of a new mid-size multi-hull AUV, the *Deep-C* AUV. The *Deep-C* AUV uses a PEMFC stack with gaseous storage of oxygen (250 bar) and hydrogen (350 bar) [45].

In 2009, French researchers from the French Research Institute for Exploitation of the Sea (ifremer) have demonstrated operation of the *Idef*[x] AUV. This AUV is powered by a PEMFC with gas storage at 250 bar (O_2) and 300 bar (H_2).

During the 2010s, further research and development projects have been carried out. Notable examples of these projects include work on a PEMFC with 110 bar gas storage [46], on a pure-oxygen fed PEMFC stack especially designed for AUVs [47], on a new high-efficiency PEMFC (at JAMSTEC) [48, 49], and on a new PEM-based fuel cell system (at the Norwegian Defense Research Establishment, FFI). However, all of these projects have been limited to isolated operation of the fuel cell system on test benches and in testing pools.

Early in 2020, Cellula Robotics Ltd. has started field trials with their new PEMFC-powered *Solus-LR* AUV. The *Solus-LR* uses high-pressure gas storage for both hydrogen and oxygen, with a stated 250 kWh useable energy, enabling missions of up to 2000 km in length.

An overview of these selected FC-AUVs is given in Table 3.1. More comprehensive reviews of FC technology for AUVs have been published by [50, 51].

Table 3.1: AUVs powered by PEM fuel cell systems

AUV	Power	Energy	Battery	Range	H_2	O_2
Urashima	4 kW	N/A	Li-ion	300 km	Chemical[a]	Gas
DeepC	3.6 kW	140 kWh[b,c]	Li-ion	400 km	Gas	Gas
Idef[x]	1.5 kW	36 kWh[b,c]	Li-ion	N/A	Gas	Gas
Solus LR	1.2 kW	250 kWh[b,c]	Li-ion	2000 km	Gas	Gas

[a] metal hydride storage
[b] useable electrical energy
[c] excluding auxiliary battery system

Being air-independent, fuel cell systems for AUVs rely on the external supply of oxygen. This supply is provided to the cell stacks either directly in the form of pure oxygen or via an artificial atmosphere (air-breathing FCs only). In case of the latter, the complete fuel cell system, i.e. the cell stacks and auxiliary components, are

placed in a pressure housing, in which an artificial atmosphere with approximately 21 % oxygen content is maintained. In such a configuration, the oxygen content is kept constant through supply of pure oxygen to the artificial atmosphere, not the stack itself. This concept is illustrated in Fig 3.3.
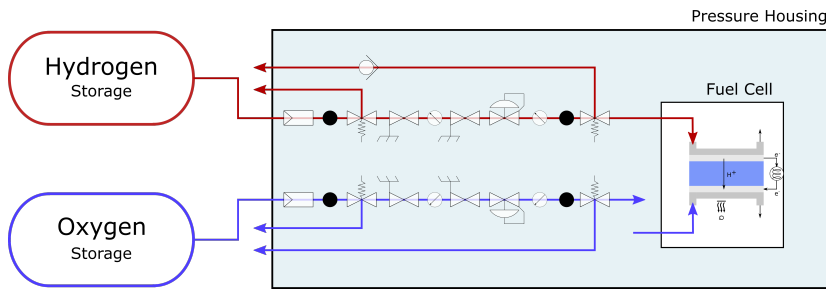

Figure 3.3: Implementation diagram for an air-breathing fuel cell (FC) in AUVs. Hydrogen is supplied directly to the fuel cell stack, whereas pure oxygen is used to maintain an artificial atmosphere in the pressure housing.

Fuel cells can provide high energy density but lack the ability to react quickly to dynamically changing loads. In order to cope with sudden peaks in power consumption, fuel cells are typically paired with secondary batteries. In these fuel cell/battery-hybrid vehicles, the fuel cell acts as the primary power source, delivering a base power within a certain limited range. Sudden increases in power demand and power demands that go beyond the fuel cell's maximum power rating, are met by the auxiliary battery system. This way, the fuel cell can be operated close to its maximum efficiency point. During phases of lower power demand, the fuel cell typically charges the battery system towards a desired state of charge (SoC) (Fig 3.4).

3.2.2 Energy Management Strategies for Fuel Cell/Battery Hybrid AUVs

Hybrid power systems consisting of two or more power sources require dedicated controllers for joint operation of the power sources. These controllers determine the power split according to specific energy management strategies (EMSs). Typically, the EMS fuses information about both the electric load and the state of the individual power sources to determine the load split (Fig 3.5). The state of the power sources is defined by parameters such as the SoC, state of health (SoH), and the respective instantaneous power output.
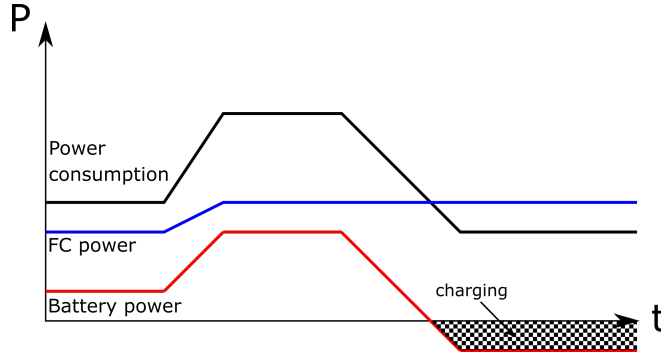
Figure 3.4: Example of a power split between two power sources. FCs provide the base power, whereas the auxiliary battery system meets the peak power demands. A surplus in fuel cell power output is used to recharge the batteries.

The goals of the EMSs can range from achieving high energy efficiency to ensuring power reliability to minimising system degradation. While the latter is mainly a cost factor (in terms of life cycle analysis), both energy efficiency and power reliability are prerequisites for long-range AUV operation. Energy efficiency allows for long-range travel by maximising the fuel utilisation, whereas power reliability helps avoiding the premature abortion of a mission due to the vehicle not being able to operate as defined in the mission plan. Power reliability is ensured by maintaining a sufficiently high SoC of the auxiliary battery system.

The two simplest and most widespread types of EMSs are rule-based and optimisation-based methods. Rule-based methods can be divided into deterministic methods (e.g. finite-state machines or look-up tables) and Fuzzy logic-based methods (multi-valued logic). Optimisation-based methods generally use local optimisation to determine the optimal power split given an optimisation problem of the following form:

$$
\begin{aligned}
\min_{P_{\text{FC}},\, P_B} \quad & f(P_{\text{FC}}, P_{\text{B}}) \\
\text{s.t.} \quad & P_{\text{req}} = P_{\text{FC}} + P_{\text{B}}, \\
& P_{\text{FCmin}} \leq P_{\text{FC}} \leq P_{\text{FCmax}}, \\
& -\left(\frac{\partial P_{\text{FC}}}{\partial t}\right)_{\text{max}} \leq \left(\frac{\partial P_{\text{FC}}}{\partial t}\right) \leq \left(\frac{\partial P_{\text{FC}}}{\partial t}\right)_{\text{max}}
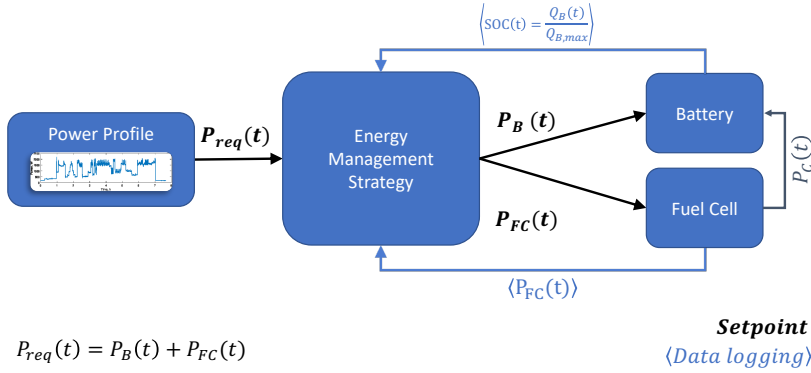\end{aligned}
\tag{3.1}
$$

Figure 3.5: Operating principle of energy management strategies (EMSs) for hybrid power systems. The EMS uses information about the instantaneous power consumption and the state of the power sources to determine the power split.

Optimisation problems of this kind minimise a cost function $f(P_{\text{FC}}, P_{\text{B}})$ under the constraints that the power demand P_{req} must be met, the fuel cell power must not exceed its operating range, and the fuel cell is not ramped up or down too rapidly. Additional constraints can e.g. limit battery discharge rates. The cost function $f(P_{\text{FC}}, P_{\text{B}})$ can be linear or non-linear (typically quadratic). Given the current state of the power system, the cost function determines the power split by penalising the use of one power source and favouring the use of the other.

Both the design and performance evaluation of energy management strategies requires sufficient understanding of the power consumption of AUVs. EMSs are usually designed without prior knowledge of the driving cycle, since driving cycles are typically not known a priori. Unlike for automotive development, the use of standard driving cycles is not feasible for the development of EMSs for AUVs, since the power dynamics of AUVs can differ significantly from mission to mission. The lack of knowledge of the driving cycles poses a challenge for the evaluation of EMSs. Two possible solutions to face this challenge are the use of recorded mission data and the use of simulated power data as reference cycles.

Therefore, field trials were performed with a *Hugin* 3000 AUV to study the power consumption and provide data for the evaluation of EMSs. The performed mission consisted of a series of different maneuvers, including standard maneuvers such as lawnmower patterns and dive cycles. The recorded power consumption shows highly dynamic power characteristics (Fig 3.6).
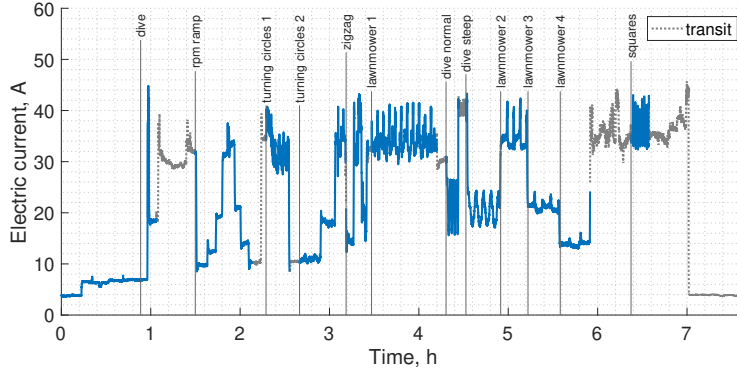
Figure 3.6: Power profile from field trials with a *Hugin* 3000 AUV

As shown in Sec. 1.2.1, the sum of propulsive power and hotel load constitutes the overall power consumption. Statistical (correlation) analysis has shown, that the dominant load contributing to the characteristic power dynamics is the motor power and thus the propulsive power (correlation coefficient $\rho = 99.4\%$). From this strong correlation between power dynamics and propulsive power, it is motivated, that the load characteristics from different maneuvers can be combined to generate new power profiles for the evaluation of EMSs. Paper D exploits this fact and uses the originally sampled power profile and two additionally generated power profiles to evaluate the performance of four different EMSs in a high-fidelity Simulink® simulation model.

The performance analyses (Paper C and Paper D) show that optimisation-based EMSs provide superior load-following behaviour of the FC system, compared to rule-based methods. Good load-following behavior is a key to unlocking high grades of power reliability by better maintaining sufficient battery SoC. However, there is a trade-off between load-following behaviour and energy efficiency of the FC system. The FC system's energy efficiency is maximised by steady operation of the FC at its maximum efficiency point. Dynamic load-following of the FC system sacrifices energy efficiency in favour of maintaining battery SoC through the conversion of hydrogen into electricity with subsequent storage in the battery system. Rule-based methods are easily tuned to provide rather rigid (or close to zero) load-following behavior and can therefore provide best energy efficiency. As such, rule-based methods are suitable for the operation of FC-AUVs on missions, which are characterised by low uncertainty and low risk.

3.2.3 Performance of Fuel Cell/Battery Hybrid Systems for AUVs

The performance of fuel cell/battery hybrid systems is characterised by mainly their energy density (energy capacity per unit volume) and specific energy (energy capacity per unit mass). Therefore, a performance assessment of fuel cell/battery hybrid systems for AUVs requires sufficient knowledge about both weight and size of all components. Analogously to the energy capacity of Li-ion batteries, the energy capacity of a fuel cell/battery hybrid system can be investigated considering the complete fuel cell system, the auxiliary battery system, and the reactants storage (hydrogen and oxygen). At the current state of fuel cell technology, such an investigation is best accomplished on an individual basis in design studies.

In flooded hull-type AUVs, all systems need to be either pressure-tolerant or stored in pressure housings, which are usually of cylindrical shape with flat lids to fit subsea connectors. A major disadvantage of using Li-ion batteries on underwater vehicles is the induced weight, which has significant adverse effects on the energy systems' effective energy density (due to the need for additional buoyancy foam to achieve neutral buoyancy). Furthermore, a junction box is needed to connect multiple battery tubes in parallel or series.

For fuel cell systems, the overall energy density depends on both the physical dimensions of the fuel cell system and the efficiency of the reactants storage. Paper E presents the design of a fuel cell system for AUV *LoLo* (c.f. Paper A), which has been designed as part of a feasibility study. This FC system design is combined with a market analysis of commercially available high-pressure hydrogen and oxygen gas cylinders to estimate the energy density of the FC system. Fig. 3.7 presents examples of the best performing configurations (Li-ion batteries and fuel cell/battery hybrid systems).

The study shows, that the vehicle endurance can be increased significantly by converting the energy system from Li-ion batteries to a fuel cell/battery hybrid system. High pressure gas storage - as opposed to e.g. metal-hydride or liquified gas storage - is a rather simple and yet efficient way of storing both oxygen and hydrogen. The advantage of using high-performance gas cylinders is two fold; gases cannot only be stored at higher pressures but also at a lower weight, which can effectively reduce the need for buoyancy foam, allowing significant volume savings and therefore further gains in energy capacity.
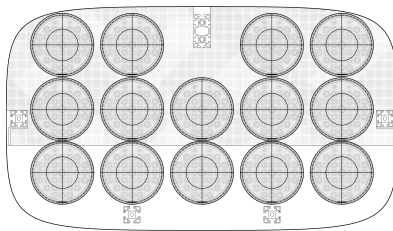
(a) Battery power system (NCR18650GA) with a total energy capacity of $56.5\,\text{kWh}$ at an energy density of $153\,\text{kW}\,\text{h}\,\text{m}^{-3}$. The shaded area represents $120\,\text{L}$ of syntactic buoyancy foam required to compensate for the weight of the batteries.
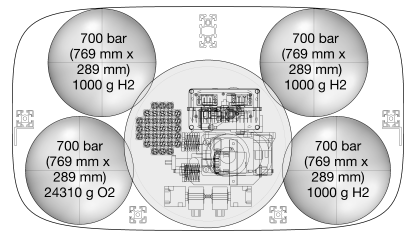
(b) Fuel cell/battery hybrid system with gas storage at $700\,\text{MPa}$. The total energy capacity is $106\,\text{kWh}$ at an effective energy density of $414\,\text{kW}\,\text{h}\,\text{m}^{-3}$ (including volume savings due to providing net buoyancy).

Figure 3.7: Comparison of the identified best-performance solutions of Li-ion battery and fuel cell/battery hybrid systems for AUV *LoLo*

Chapter 4

Conclusions

4.1 Contributions to the Field

Paper A

Paper A presents the design of a versatile and modular AUV that forms the basis for subsequent design studies and experimental validation. A robust hierarchical captain-scientist software architecture is proposed for the safe integration of new technologies (both hardware and software) and the safe operation by scientists. An extra large payload bay allows for implementation of various sensors. The large energy bay is designed to store a maximum of ca. $40\,\mathrm{kWh}$ of electrical energy in Li-ion battery packs, enabling long-range underwater operation.

Paper B

Paper B addresses a long-disputed topic in underwater robotics: Do gliders really have an inherently better range capability than propeller-driven AUVs? In order to answer this question, the energetics of flight of both propeller-driven and buoyancy-driven underwater vehicles are analysed. The analysis yields a glide coefficient

$$C_{GL} = \frac{C_D\left(C_D^2(\alpha) + C_L^2(\alpha)\right)^{3/2}}{C_L^3(\alpha)}, \qquad \text{(2.28 revisited)}$$

which can be used to express the average propulsive power of underwater gliders projected onto the horizontal trajectory only. Under consideration of the individual system's mechanical efficiency, the initial question on glider efficiency can be answered by comparing the propulsive power of propeller-driven and buoyancy-driven systems using the glide coefficient and a bare-hull drag coefficient. Assum-

ing identical size of buoyancy engine and propeller drive train, it becomes evident, that the superiority of one propulsion system over the other is design-dependent, since the glide metric is a function of the non-dimensional hydrodynamic coefficients and the system's mechanical efficiency.

Furthermore, an intermediate-fidelity flight mechanics model is proposed for both underwater gliders and propeller-driven AUVs. At initial design phases, the model can be used to estimate the hydrodynamic coefficients and perform parametrised design optimisations. The model is validated using hydrodynamic coefficients from published CFD-analyses of the legacy underwater glider *Slocum*.

Paper C & Paper D

In Papers C & D, the performance of energy management strategies (EMSs) for AUVs is evaluated. Hybrid power systems such as fuel cell/battery hybrid systems require an EMS to determine the power split.

In Paper C, four EMSs are presented, of which two are rule-based and two are optimisation-based. A new quadratic cost function for optimisation-based EMSs is proposed, which uses the desired values for fuel cell power (typically the maximum efficiency point) and battery state of charge as target values. The performance of the EMSs is evaluated against a power profile which has previously been sampled with a *Hugin 3000* AUV.

Paper D builds upon Paper C and involves both more power profiles and high-fidelity simulation models. The power profile from Paper C is analysed and segmented into different maneuvers. These individual segments retain their characteristic power dynamics and, since power dynamics correlate strongly with maneuvering dynamics, can be used to generate additional power profiles. A high-fidelity simulation model of the fuel cell/battery hybrid system is developed in Simulink®, allowing for capturing of all relevant dynamic behaviour of both the Li-ion battery and the fuel cell system.

The performance evaluation shows that essentially both types of EMSs, rule-based and optimisation-based, have disadvantages and advantages. Optimisation-based methods have superior load-following behaviour, which leads to a better conservation of battery state of charge. Maintaining battery state of charge can be beneficial in terms of battery degradation, but, most of all, a sufficiently high battery state of charge represents power reliability. Low battery state of charge risks compromising mission and operation integrity. As such, optimisation-based methods are the preferred choice of EMS for missions, where mission success is

not limited by energy capacity but by system autonomy. In contrast, rule-based methods are easily tuned to operate at a maximum (energy) efficiency point and there provide better fuel economy.

Paper E

Paper E focuses mostly on the benefits of using fuel cell systems on underwater vehicles, but also reveals some of the challenges. Through the preliminary design of a fuel cell/battery hybrid system for AUV *LoLo*, the foundation is laid for the performance evaluation and comparison of pure Li-ion and fuel cell/battery hybrid systems. The role of induced weight of the power system is highlighted: Battery systems are intrinsically heavy and always require additional buoyancy foam to achieve neutral buoyancy. On the contrary, fuel cell systems do not only offer high energy density, but - being rather light but voluminous systems - provide net buoyancy and can replace or even diminish the need for buoyancy foam.

A market analysis is performed to identify the current state-of-the-art of hydrogen and oxygen gas storage. The analysis shows that both Type III and IV gas cylinders are performing well as candidates for application on AUVs. Using commercial components only, it is shown how the combination of high-quality gas cylinders with the proposed fuel cell system for AUV *LoLo* can increase the vehicle's energy capacity by 20 % at an even higher energy density.

However, being a rather unusual application, these gas cylinders are not designed for use in underwater application and the subjection to external pressure. This circumstance requires further investigation and poses a challenge regarding implementation of fuel cell systems on AUV. Another challenge is of infrastructural nature and concerns the implementation of hydrogen-powered vehicles into existing lab infrastructure and vehicle fleets (e.g. refuelling during research cruises).

4.2 Future Work

In the future, the demand for long-range autonomous underwater vehicles is likely to increase even further as increased range will undoubtedly be beneficial for all AUV operators. This doctoral thesis has presented several valuable performance assessments and design studies regarding long-range AUV technology. As such, this research not only forms a good basis for future research to build on, but also leads to further research ideas.

4.2.1   Fuel Cell Systems for AUVs

With electromobility growing fast, research on energy systems for long-range AUVs can be expected to converge towards better and better solutions. As was shown in this thesis, fuel cell systems are a promising alternative to electrochemical batteries as power sources for AUVs.

Future research needs to include the development of a prototype FC system for air-independent operation. The development of such a prototype will also facilitate the implementation and evaluation of energy management strategies in experimental field trials. Future research will also have to address the optimisation of FC stacks and other components. By optimising the system components, a more compact pressure-housed fuel cell system can be designed. Combining an optimised FC system with state-of-the-art reactants storage will provide an overall superior energy capacity.

The storage of reactants (hydrogen and oxygen) is another important research topic. Unlike AUVs, military manned submarines use liquified oxygen and chemical storage (metal hydrides) or hydrocarbon reforming for the supply of hydrogen. It remains to be investigated, whether these storage solutions can further enhance the range of AUVs.

Current investments in hydrogen energy will likely lead to more development and better availability of FC components. Assuming that FCs will become an easily accessible technology in the near future, life-cycle analyses/comparisons of both Li-ion and FC power systems will be part of future work. On top of life-cycle assessments, the integration of hydrogen technology into existing fleets and infrastructure will also be an important field of development.

4.2.2   Underwater Propulsion

The design of efficient underwater propulsion systems and their integration into different vehicle designs is a key technology to long-range cruising of AUVs.

Buoyancy engines are the mechanical components that enable underwater gliding. As such, the propulsive power of underwater gliders is dependent on the mechanical efficiency of the buoyancy engine. Future work needs to consider a review of the design of high-efficiency buoyancy engines. In the past, several designs and concepts have been published, including extendable pistons, oil-bladders (closed system), and ballast tanks (open system). The development of high-efficiency buoyancy engines is a key to energy-efficient underwater gliding.

Besides underwater gliding, another type of unconventional propulsion needs to be investigated further: biomimetic or bio-inspired underwater propulsion. This form of propulsion aims at reproducing mechanisms of locomotion used by aquatic animals. Through evolution, aquatic animals have developed highly efficient means of locomotion [52, 53]. There are four main forms of aquatic locomotion underwater: Undulatory swimming, oscillatory swimming, and pulsatile jet locomotion [54, 55]. Particulary interesting for the adaptation on robotic platforms are locomotion forms used by natural long-range swimmers, e.g. whales and manta rays.

However, the development of biomimetic and bio-inspired underwater vehicles is still an ongoing field of research. The challenge in the development of bio-inspired robots lies in the efficient design of mechanical systems for reproduction of the required undulating or oscillatory motions. Besides potential additional benefits, the feasibility and propulsive efficiency of biomimetic propulsion systems for AUVs remains to be investigated experimentally.

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